The Properties and Behavior of Disturbances in the Frequency Range 9 kHz to 150 kHz Produced by Household Appliances in a Residential Network Environment

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Kurzfassung

Viele Haushaltsgeräte sind mit Inverter-Technik ausgestattet, welche Störungen im Frequenzbereich zwischen 9 kHz und 150 kHz erzeugen kann. Der Standard zur Vermeidung dieser Störungen in diesen Frequenzbereich deckt nicht alle Haushaltsgeräte ab und die Bemühung diese für einige Haushaltsgeräte einzuschränken ist gering. Die durch Haushaltsgeräte produzierten Störungen können die Betriebsleistung anderer im selben Netz angeschlossener Geräte beeinflussen. Ebenfalls können benachbarte Haushaltsgeräte durch ihre internen Eigenschaften die Störungen beeinflussen. Einige Phänomene bezüglich der Interaktion der Störungscharakteristik zwischen den Haushaltsgeräten wurden zwar von einigen Forschern festgestellt und publiziert, aber noch keine weiteren Analysen wegen der begrenzten Kenntnis über die Störungscharakteristik durchgeführt.

Diese Arbeit untersucht an Hand von Beobachtungen die Eigenschaften und das Verhalten der Störungen im Frequenzbereich zwischen 9 kHz und 150 kHz von Haushaltsgeräten in der Umgebung von Haushaltsnetzen in Wohngebäuden. Die Störungseigenschaften und das Verhalten sind wichtig zur Prognose und Ermittlung der im Netzwerk erzeugten Störungen. Der Effekt einiger Parameter in Netzen von Wohngebäuden auf die Störungen sowie die Variation der Netzspannung und Netzimpedanz, als auch die Anwesenheit von benachbarten Geräten, werden untersucht. Diese Untersuchungen bestehen aus vier Hauptteilen: Der Erste identifiziert die internen Impedanz-Eigenschaften der Geräte. Der Zweite definiert die Störungseigenschaften sowie das Verhalten der einzelnen und gleichzeitig betriebener Geräte. Der Dritte simuliert die Störung von Geräten im Haushaltsnetzwerk für den gleichzeitigen Betrieb. Der Letzte behandelt die Prüfung von existierenden Standards für Störungen im Frequenzbereich von 9 kHz bis 150 kHz im vergleich mit realen Zuständen in Haushaltsnetzen. Die Testprüflinge, die in dieser Untersuchung verwendet werden sind: ein Induktionsherd, Inverter-Mikrowelle, konventionelle Mikrowelle, Mixer, Stab Mixer, Wasserkocher, Desktop-Computer, Notebook, Flachbildschirm mit LED-Technik, Föhn, elektrisches Massagegerät, Bügeleisen, Kompaktfluoreszenzlampe und eine LED Lampe.

Die Störung, die durch jedes Haushaltsgerät im Frequenzbereich von 9 kHz bis 150 kHz emittiert wird, hat einzigartige Eigenschaften und Verhalten. Die Störung wird beeinflusst durch die Anwesenheit von benachbarten Haushaltsgeräten im Netz. Die benachbarten Geräte können, in Abhängigkeit ihrer Leistungsaufnahme und internen Impedanz-Eigenschaften, die im Netz auftretenden Störungen verstärken oder abschwächen. Zusätzlich werden die Netzspannung und die Netzimpedanz durch die Variation der Störungen beeinflusst. Einige Situationen in realen Haushaltsnetzen können zu Unterschieden zwischen den Standard Emission Tests und den realen Netzbedingungen führen. Der Nutzer sollte sich bewusst sein, dass die in diesen Situationen auftretenden Emissionen von den realen Bedingungen unterschiedlich sein können.

Abstract

Many household appliances are equipped with inverter technology which may generate disturbances in the frequency range 9 kHz to 150 kHz. Since the standards managing the disturbance in this frequency range are not covering all household appliances, the effort to limit the disturbance produced by some appliances become less. The disturbance produced by the appliance may influence the operation performance of neighbor appliances which are connected to the same network. In the other hand, the neighbor appliances due to their internal properties may also influence the disturbance produced by the appliance. Some phenomena regarding the interaction of disturbance characteristics between appliances have been recognized and reported by some researchers, but no further analysis can be done due to the limited knowledge about this disturbance characteristics.

The study focuses on observing the properties and behavior of disturbances in the frequency range 9 kHz to 150 kHz produced by some household appliances in a residential network environment. The disturbance properties and behavior are important to predict and investigate the disturbance occurred in the network. The effect of some parameters of residential network environment to the disturbances are observed including the variation of mains voltage level, the presence of neighbor appliances and the variation of mains network impedance. There are four main works conducted in this study, the first is identifying the internal impedance properties of appliances, the second is defining the disturbance properties and behavior for individual and simultaneous operation of appliances, the third is simulating the disturbance for simultaneous operation of appliances in residential network environment, and the last is reviewing the existing standards of disturbance in the frequency range 9 kHz to 150 kHz corresponding to the real residential network situations. The equipment under test used in this study are induction cooker, inverter microwave, conventional microwave, mixer, hand blender, water cooker, personal computer, notebook, television LED, hair dryer, electric massage, iron, compact fluorescent lamp and LED lamp.

The disturbance emitted by each household appliance in the frequency range 9 kHz to 150 kHz has unique properties and behavior. The disturbance is affected by the presence of neighbor appliance in the network. The neighbor appliances, depending on their power consumption and internal impedance properties, may increase or decrease the disturbance occurred in the network. Besides, the mains voltage level and the mains network impedance variation are also influencing the disturbance. Some conditions in the real residential network environment may lead to the difference of disturbance obtained in the standard emission test and the real network environment. The user should be aware that there are situations in which the emission occurred in the field could be different.

Contents

CHAPTER 1
INTRODUCTION

1.1. Overview

Nowadays, many household appliances implement inverter technology due to some benefits of smaller size, lighter weight, better performance, and energy saving. The inverter technology used by household appliances generally has switching frequency in the range 9 kHz to 150 kHz which is consequently generating the disturbance in that frequency range [1]. In the past, the research on the disturbance in the frequency range 9 kHz to 150 kHz was not popular due to the rare sources of disturbance and the problem related to this disturbance was not widely documented [2,3,4]. Since the negative effects of this disturbance to electronic energy meter and automatic meter reading operations are reported and the increasing use of technology that is generating the disturbance in many household appliances, the research in this frequency range starts to get more attention. Referring to the observation conducted by some researchers, several household appliances including PV inverter, compact fluorescent lamp, led lamp and induction cooker are recognized of producing the disturbance in the frequency range 9 kHz to 150 kHz [3,4,5,6]. The list of household appliances which are identified emitting the disturbance in this frequency range can be seen in Table 1.1.

Table 1.1 The household appliances emitting disturbance in the frequency range of 9-150 kHz (Source: [6])

Type	Example Appliances
Inverters	PV installations
Switch-mode power supplies	Lighting equipment, PCs, consumer electronic/home entertainment equipment (e.g. TV, DVD), ICT equipment, uninterruptible power supplies (UPS), charging devices
Lighting equipment	Fluorescent lamps, compact lamps, LEDs
Household equipment	Induction cookers, washing machines, Inverter Based Microwave

In the shared low voltage network like residential network environment, many appliances can be connected to the network and operated simultaneously. The disturbance produced by one appliance may influence the operation performance of other appliances connected to the same network [7,8]. Through the observation and investigation, some researchers reported several effects of the disturbance to the operation performance of appliances. The current disturbance produced by PV inverter can influence the electronic energy meter causing a significant error in the meter reading [9]. Other negative effects of this disturbance on the operation performance of household appliances have been also documented as shown in Table 1.2

Table 1.2 The effect of disturbance in frequency range of 9-150 kHz to the operation of some household appliances (Source: [6])

Appliances	Effect
Notebooks	Disturbed cursor position (37 kHz)
Coffee cooker	Incorrect control lamp function
Washing machines	Self-restart (some hours) after end of operation phase
TV and radio receiver	Audible noise (up to 20 kHz)
TDLs	Unintentional switching (between light steps, OFF, also ON)
ADSL modem	Loss of link, CRC error

To ensure the compatibility level between appliances, some standards related to the emission limit in the frequency range of 9 kHz to 150 kHz exist. There are 2 types of products used in households, for which the product standard defines the limits, the lighting equipment and induction cooker. The lighting equipment emission limit is covered in DIN EN 55015 (CISPR 15) while the induction cooker emission limit is stated in DIN EN 55014 (CISPR 14). According to the DIN EN 55015 [10], the emission limit for lighting equipment in the frequencies 9 kHz to 50 kHz is 110 dBµV and it is getting down from 90 dBµV to 80 dBµV linearly with logarithm of frequency for the range between 50 kHz – 148.5 kHz. The emission limit standard of induction cooker as stated in DIN EN 55014 [11] are identical to the emission limit for lighting equipment in DIN EN 55015. Figure 1.1 shows the emission limit curve for both standards mentioned above.

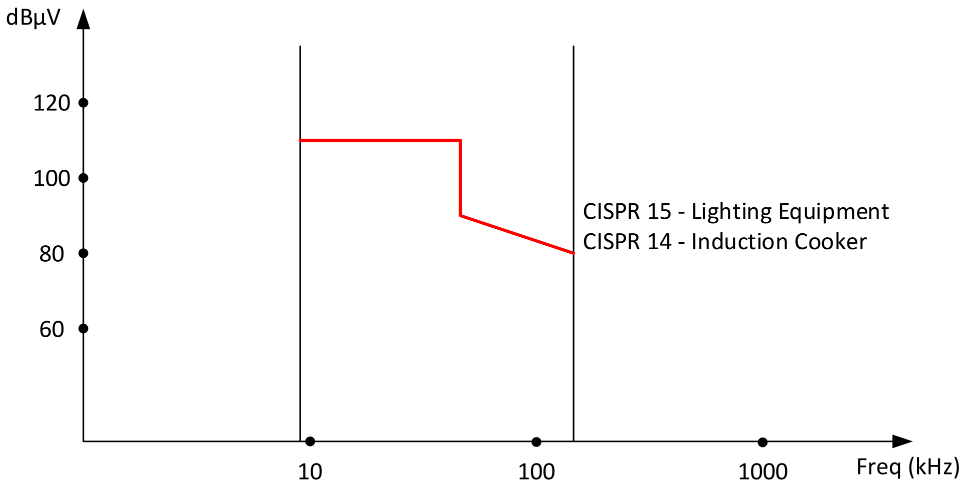


Figure 1.1 The emission limit of lighting equipment and induction cooker in the frequency range 9-150 kHz

The emission test described in the standard is performed by operating the EUT individually at the nominal voltage level in controlled mains network [12,13,14]. The artificial mains network (AMN) is used to control the impedance seen by the EUT and decouples the EUT from the mains network. The actual emission appeared in the network when the EUT is operated in real network situations could be different due to the influence of some factors existing in the real network environment. Three main situations which are normally occurring in the real network environment are the variation of mains voltage level, the presence of neighbor appliances and the variation of mains network impedance.

The supply voltage level provided in the low voltage network normally varies over the time due to some factors including the variation of load connected to the network. The standard EN 50160 defines requirements for the supply voltage level variation tolerance in the public distribution system [15]. The supply voltage variation is limited to ±10% of the nominal voltage level, hence when the nominal voltage used is 230 V, the lowest permitted supply voltage level is 207 V. The voltage level variation is very common and can easily occur in real residential networks. For example, in one household customer, when there is no appliance connected to the power outlet, the utility voltage level is 230 V. The voltage level then drops to 227 V when one powerful appliance is operated. Furthermore, when another powerful appliance is then also connected to the same network, the voltage level can drop further to 224 V. This condition shows that the load variation (depend on their power consumption properties) may easily change the mains voltage level. The variation of voltage level may affect the disturbance produced by the appliances.

Hence, the emission test performed only at nominal voltage level as required in standard emission test may not provide the highest possible disturbances produced by the EUT.

The simultaneous operation of appliances normally occurs in public residential networks. When one appliance is operated and connected to the power outlet in the building, it may generate and emit a disturbance to the network. The operation of other appliances (neighbor appliances) connected in the same network consequently will draw current and connect their internal impedances to the network. The properties of power consumption and internal impedance of the neighbor appliances may influence the disturbance occurring in the network. In the frequency range 9 kHz to 150 kHz, some household appliances that are equipped with EMC filter have very low impedances which may provide paths for intentional and unintentional signals in that frequency range [16]. The observation of disturbance behavior for simultaneous operation of appliances has been conducted and reported by some researchers. The simultaneous operation of photovoltaic power generation, electric vehicle and some household appliances have indicated that the disturbance produced by the appliances in this frequency range is only propagating between appliances and not flowing to the network grid, meaning that the neighbor appliances filter the disturbance occurring in the network [3,4]. The measurement of simultaneous operation of 48 fluorescent lamps is also resulting in the same condition that the disturbance is propagating between the lamps rather than upstream to the network grid [17]. Slightly different results were obtained by other observation that the disturbance which is produced by appliance and appeared in the network may be either attenuated or amplified by the presence of the neighbor appliances in the same network [5]. Previous research showed that the disturbance generated by individual appliances has specific properties and behavior and it may be influenced by the presence of neighbor appliances. This condition indicates that the emission test for individual operation of appliances may not give the real possible disturbance occurred in the real shared networks.

The mains network impedance is related to the electrical equipment used to distribute the power and the customer appliances connected to the network. The internal impedances of customer appliances in the frequency range 9 kHz to 150 kHz are unique and may consist of RLC components. Hence, the network impedance viewed at one customer network may contain series and parallel resonances at certain frequencies. This condition may cause the real mains network impedance to consist of inductive and capacitive contributions for certain frequencies in the range within 9 kHz to 150 kHz. However, the standard emission test uses the artificial mains network (AMN) which has only inductive properties in the frequency range between 9 kHz to 150 kHz. The presence of capacitive properties in the real mains network impedance may cause the disturbance appearing in the network to be higher than it is measured in standard test configuration.

Referring to the explanation above, it can be concluded that the disturbance produced by the appliances in the network depends on internal and external factors. The internal factors are related to the disturbance properties and the internal impedance of the appliance while the external factors are related to the network characteristics including the mains voltage level variation, the presence of neighbor appliances and the mains network impedance variation. Due to the variation of those real network properties, the emission test of single operation of appliances in controlled network condition may not give a reliable prediction of disturbance in the real network environment [3,8]. Hence, further observation about the effect of both internal and external factors to the properties and behavior of disturbance produced by household appliances in the real network environment are necessary.

1.2. Motivation of Work

The recent situation of the standards and the research related to the disturbances in the frequency range 9 kHz to 150 kHz for household appliances has been briefly explained in the introduction section. It can be noticed that some issues are still needed to be observed and identified further. The issues can be classified in some points below:

A. The limited knowledge about the disturbance properties and behavior

The research on this frequency range is starting to become popular. Some facts and phenomena regarding to the disturbance characteristics have been recognized, but many works are still needed to identify and determine the disturbance properties and behavior which should be beneficial for investigating and predicting the disturbance occurred in the network. To figure out the phenomena of disturbance occurring in the real network environment, three main properties should be identified, the properties and behavior of disturbances produced by individual appliances, the characteristics of internal impedance of appliances, and the properties of mains network environment.

B. The possible issues related to the standard emission test procedures

The emission test regulated in the standard is performed by operating the appliance in the specific condition and configuration. The actual emission when the appliances are operated in the real network could be different due to the influence of some factors existing in the real network environment. Some potential issues related to the existing emission test procedure are as follows:

- **The test is performed only at the nominal voltage level.**

  The standard EN 50160 defines the requirements for the supply voltage level variation tolerance of ±10 % to the nominal voltage in the public distribution system. For some appliances, the produced disturbance may be affected by supply voltage level due to their working operation characteristics. Since the standard emission test as described in EN-55011 [13] only requires the test at nominal mains voltage level, the highest possible disturbance produced by the appliance may not be obtained from the test. To observe the effect of supply voltage level to the disturbance produced by appliances, the measurement of the disturbance produced by some household appliance at different supply voltage levels should be performed.

- **The test is performed for individual operation of appliance**

  The disturbance generated by individual appliance may be influenced by the presence of neighbor appliances. Since in the real residential network many appliances may be operated and connected to the same network, then the disturbance (emission) test of individual operation of appliance may not give a reliable prediction of disturbance in the real network environment. The disturbance appeared in the network may be higher when it is operated simultaneously with the neighbor appliances. To identify the effect of neighbor appliances to the disturbances, the simultaneous operation of appliances in the shared network should be conducted.

- **The equipment under test is connected to artificial mains network**

  In the real network condition, the impedance of mains network normally varies and has specific properties that may cause the disturbance occurring in the real network to be higher than in the artificial mains network. To explore the effect of the mains network on the disturbance occurring in the network, 5 residential network impedances at different periods (low and peak load periods) will be measured. These measured residential network impedances will be used to simulate the disturbance characteristics in the real mains networks.

- **The use of conventional test receivers.**

  The disturbances produced by some appliances may not be constant over the time due to their working characteristics. When the disturbance produced by appliance is decreased over the time, then the highest disturbance will be occurred at the beginning time of appliance operation. The conventional frequency stepped scan test receiver that can still be used in the emission test normally requires a couple of time to perform the measurement (the time needed is depending on the frequency range of the test). Due to this condition, the disturbance measured using conventional test receiver may not obtain the highest potential disturbance produced by appliance when the disturbance produced by the appliance decreases over the time. Although newer receivers (FFT-based) are now allowed for the measurements, the standards do still not make use of the special features of this type of receivers.

Some predefined issues related to the existing standard emission test in the frequency range of 9 kHz to 150 kHz are needed to be observed. By referring to the properties and behavior of disturbance in the real network condition obtained from this study, some considerations and recommendations may be necessary to improve the existing standard emission test.

1.3. Scope

The study is focused on observing the properties and behavior of disturbance in the frequency range 9 kHz to 150 kHz produced by household appliances in low voltage residential network. Due to the low frequencies of disturbances, the observation will be limited to differential mode disturbances. The measurements are performed both in a laboratory with definite environmental properties and in a real residential network environment. Two software tools used in data processing and simulation are MATLAB and LTSpice. The equipment under test chosen for this study are some household appliances including induction cooker, inverter microwave, conventional microwave, mixer, hand blender, water cooker, personal computer, notebook, television LED, hair dryer, electric massage, iron, compact fluorescent lamp and LED lamp.

1.4. Thesis Layout

The first chapter gives a short overview about the research, motivation, scope and the contribution of the work.

The second chapter gives a brief description of conducted disturbances and the selection of equipment under test. The testing and simulation setups are also explained.

The third chapter determines the properties of disturbances produced by individual operation of household appliances. There are two main properties that will be discussed, the disturbance level and disturbance frequency properties.

The fourth chapter describes the measurement of the internal impedance and defining the impedance equivalent circuit parameter of some household appliances. Combining the disturbance properties obtained in previous chapter and the internal impedance properties gathered in this chapter, the equivalent circuit of appliances could be constructed.

The fifth chapter determines the effect of neighbor appliance to the disturbance occurred in the network. The testing results are also used to validate the equivalent circuit of appliance obtained from previous section by comparing the disturbance gathered from measurement (testing) and calculation (simulation).

The sixth chapter demonstrates the simulation of disturbance in residential network environment. Three parameters that are representing the residential network situation are used and the effects of each parameter to the disturbance are discussed.

The seventh chapter discusses the evaluation of the existing standard related to the emission test procedures. The evaluation is conducted by referring the testing and simulation result of disturbance characteristics in real network situations. Some recommendations are also proposed to improve the emission test result.

Finally, the eighth chapter concludes the major results of the study.

1.5. Own Contributions

A. Properties and behavior of disturbance for individual operation of appliances

The disturbance produced by some appliances is affected by mains voltage level. There are 4 different types of correlation between the disturbance produced and mains voltage level, constant, linear, inverse and combination. This behavior should be considered when performing the emission test since the existing emission test standard only requires the test at the nominal voltage level [13].

B. Equivalent circuit parameter of some household appliances

To observe the disturbance behavior in the frequency range 9 kHz kHz to 150 kHz properly, the internal impedance properties of all appliances connected in the network should be defined. In this study, the internal impedance properties of some household appliances are identified and the equivalent circuit parameters are constructed. The internal impedance equivalent circuit can be used further to simulate and investigate the disturbance occurred in the real network environment.

C. The classification of neighbor appliance based on the effect to the disturbance

The disturbance produced by the appliance is affected by the neighbor appliances when they are connected and operated simultaneously. Generally, the neighbor appliances influence the disturbance through two ways, the first through their internal impedances properties which may filter or amplify the disturbance, the second through their power consumption properties which may cause the voltage drop in the network and lead to the increasing or decreasing the disturbance produced by the appliance. Referring to the study, the neighbor appliances are classified into 4 types concerning to their internal properties and their effects to the disturbances.

D. The evaluation and consideration for the existing emission test procedure in the frequency range within 9-150 kHz.

Based on the disturbance properties and behavior obtained from the test and simulation, some considerations and recommendations related to the emission test procedure are proposed. The evaluation of existing emission test procedure is conducted by considering 3 parameters occurred in the real network environment including the mains voltage level variation, the presence of neighbor appliances, and the mains network impedance variation.

CHAPTER 2
CONDUCTED DISTURBANCES IN RESIDENTIAL NETWORKS

2.1 Conducted Disturbances

The operation of electrical appliances generates and emits electrical signals to the power systems. There are two types of signals that can be emitted by the appliances

- Intended Signal
  This signal is intentionally generated and needed for the correct operation of the appliance. In case of PLC communication, the signal in certain frequency ranges is generated for communication purposes. This signal however becomes the disturbance for other appliances that are not involved in the communication process.

- Unintended Signal
  The emission of this signal is a waste product that is not needed for the operation of an appliance. This signal is related to the working principle of the appliance and naturally becomes a disturbance for other appliances. In case of appliances that are equipped with inverter technology, they normally generate the disturbance at the switching frequency used.

The disturbances can propagate through air and conductor resulting in radiated and conducted disturbance. The coupling path of disturbance propagation can be conductive, capacitive, inductive or radiative as shown in Figure 2.1. For low frequency range, the disturbance is normally propagating through the cable (conducted) rather than radiated from the appliance. This is due to the bigger antenna structures required for lower frequency disturbance to be radiated. Since the physical size of most appliance is relatively small, it is generally not sufficient to radiate low frequency disturbances [18,19,20].

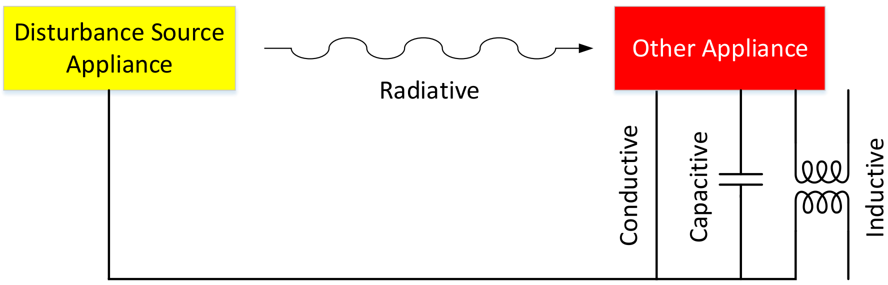


Figure 2.1 The propagation type of disturbance

The EMC standard covers the conducted disturbance from the frequency range 0 Hz to 30 MHz [19]. The first range of conducted disturbance is the harmonics range. The harmonics is unwanted disturbance signal with the frequency of integer multiple from the power system fundamental frequency. The harmonic signal is generated by non-linear loads and causing non-pure sinusoidal of power system waveform. Referring to the EN 61000-3-2 standard, the harmonics frequency range is generally up to 40^{th} order of power systems fundamental frequency. When the power systems frequency used is 50 Hz, then the harmonic frequency range is from 50 Hz up to 2 kHz.

The second set of EMC standard covers the conducted disturbance for radio frequency (RF) range from 9 kHz up to 30 MHz. The conducted disturbance of RF range is generally divided into 2 sub ranges of 9 kHz to 150 kHz and 150 kHz to 30 MHz. The lower RF range (9 kHz to 150 kHz) is currently getting more attention due to the use of this frequency range for mains communication signaling (Power Line Communication), the effect of this disturbance on the error of electronic meter reading and the increase of number and type of appliances producing disturbance in this frequency range.

Concerning the disturbance point in the power systems circuit, the conducted disturbance can occur in two modes, differential mode and common mode disturbance. The differential mode disturbance occurs between any two lines of the system (in case of single phase system, it occurs between phase and neutral) while the common mode disturbance occurs from any line in the system (phase and neutral) towards earth. At low frequency range, the mode of disturbance that generally arises in the network is the differential-mode disturbance. The common mode disturbance is not significant at low frequency range due to the high impedance of stray capacitance between line and earth. Figure 2.2 shows the differential and common mode disturbances occurring in the single-phase systems.

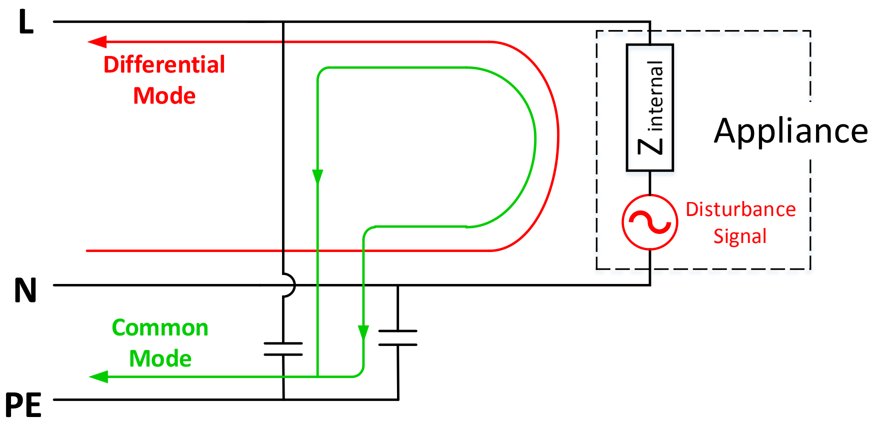


Figure 2.2. Differential and common mode disturbance in a single phase system

The study is focused on observing the properties and behavior of differential mode of conducted disturbance in the frequency range 9 kHz to 150 kHz produced by household appliances in residential network environment.

2.2 Residential Network Characteristics

Regarding the differential mode of conducted disturbance produced by appliances, some characteristics of residential networks may influence the disturbances in the network. There are 3 characteristics of residential network that normally occur in the real network situation as follows:

1. **Mains Voltage Level Variation**

   In residential network, the voltage level provided in the low voltage distribution systems normally varies over time mainly due to the variation of electrical load connected to the network. The customer loads can be dynamically connected and disconnected (on and off) causing a change of current flowing and consequently a change of the voltage drop in the distribution network.

The voltage level variation can obviously be noticed between low and peak load periods. In residential network, the low and peak load periods normally occur at day time and night time respectively. The utility voltage level (the voltage at power outlet) can easily drop when some powerful appliances are connected and operated simultaneously in the network. This voltage drop may eventually affect the disturbance produced by the appliances. The measurement of disturbances that are produced by appliances at different supply voltage level should be performed to define the distortion behavior related to the supply voltage level variations.

2. The Presence of Neighbor Appliances

The appliances have two main electrical properties, the power consumption and internal impedance. The power consumption property is related to the amount of power needed for an appliance to operate while the internal impedance property is related to the internal electrical circuit.

In the residential network environment, many appliances can be connected simultaneously to the network. At the disturbance source appliance point, other appliances which are also connected to the network are called neighbor appliances. The neighbor appliances can be classified to the local and global neighbor appliances. The local neighbor appliance is the neighbor appliance located in one customer network while global neighbor appliance is the neighbor appliance located at other customer in similar distribution network (containing some customers) as can be seen in Figure 2.3.

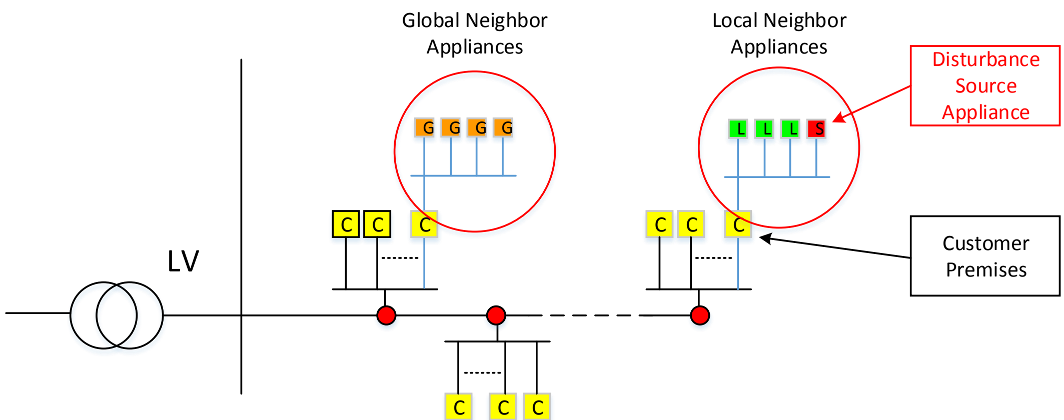


Figure 2.3 The neighbor appliance classification

The neighbor appliances depend on their power consumption and internal impedance properties may affect the disturbance in the network. The local neighbor appliances due to their near location to the disturbance source appliance will give more significant impact to the disturbance than the global neighbor appliances.

3. **Mains network impedance variation**

The mains network delivers the power to the customer appliances. The mains network has an impedance related to the electrical equipment used to deliver the power from the grid to the customer and the customer loads connected to the network. Since the distribution network configurations for every residential area is unique (depends on the network type, coverage area and load density) and the customer appliances connected to the network may also vary over the time (peak and low load period), consequently the mains network impedance properties will also vary for each area and time [21]. The impedance properties of mains network may affect the disturbance occurring in the network.

Related to the disturbance properties, the appliance can be modeled with its equivalent circuit containing specific disturbance sources and internal impedances as can be seen in Figure 2.4. The disturbance occurring in the network then will be depending on the disturbance source properties and interaction between internal impedance of appliance and mains network impedance.

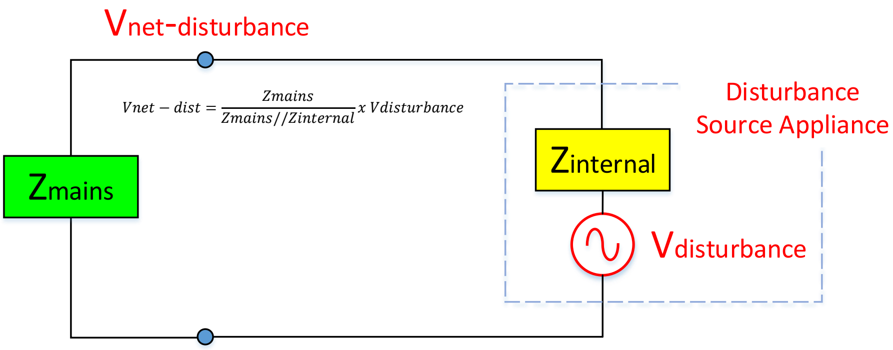


Figure 2.4 The effect of mains network impedance to the distortion

Since the residential network environment has some characteristics as explained above, the observation of disturbance properties and behavior in residential network should consider the mains network impedance properties, the behavior of disturbance related to the mains voltage level variation and the properties of neighbor appliance (power consumption and internal impedance properties).

2.3 Household Appliance Selection (EUT)

Some household appliances are reported generating disturbance in the frequency range 9 kHz to 150 kHz as can be seen in Table 1.1. The primary sources of disturbance in this frequency range are the appliances which are applying switched-mode power supplies in their working operation [18]. The switch mode power supply is a power supply that utilizes switching devices such as MOSFETs that continuously turn on and off at high frequencies to convert the power into a form needed by appliances. Besides, many conventional household appliances are also implementing inverter technology in their operation such as inverter based microwave. The disturbance normally corresponds to the switching frequency used. Since the switching frequency of inverter for household appliances is generally in the frequency range 9 kHz to 150 kHz, consequently it will also generate disturbance in that frequency range.

The study is focused on the disturbance that is produced by household appliances in residential network environment. Some household appliances will be selected as the equipment under test (EUT). Some predefined criteria used in selecting the EUT are as follows:

1. **Portable appliance**
   The test and measurement in this study will be performed in laboratory and residential location. Due consideration of ease movement of appliance, only portable household appliances will be selected as the EUT.
2. **Representing a common household appliance**
   To ensure the existence of the EUT in the real residential network, the EUT chosen should be well-known/commonly used in the household application.
3. **Having different power consumption**
   To observe the effect of power consumption characteristics to the disturbance occurred in the network, the EUT chosen should consist of mixed high and low power consumption properties.
4. **Having different internal impedance properties**
   The study will also concern the effect of simultaneous operation of appliance to the disturbance. The internal impedance of appliance is one important property that may affect the disturbance. Hence, the EUT chosen should have different internal impedance properties in the frequency range 9 kHz to 150 kHz.

Based on the criteria above, the household appliances that have been chosen as the EUT are induction cooker, inverter based microwave, conventional microwave, mixer, hand blender, water cooker, personal computer, television, notebook, hairdryer, electric massage, iron, compact fluorescent lamp and LED lamp. The technical specification of each DUT can be seen in Table 2.1.

Table 2.1 The technical specification of EUT

Nr.	Appliances	Power Consumption (Watt)	Additional Specification
1	Induction Cooker A	1600	6 Power Level Options
2	Induction Cooker B	2000	8 Power Level Options
3	Inverter Microwave	1000	4 Power Level Options
4	Conventional Microwave	1000	
5	Mixer	450	
6	Handblender	400	
7	Water Cooker	2000	
8	Personal Computer	300	
9	Notebook	90	
10	Television LED	60	
11	Hairdryer	1000	
12	Electric Massage	20	
13	Iron	2000	
14	LED Lamp A	7	470 Lumen
15	CFL A	15	820 Lumen

In the test of simultaneous operation of appliance, the household appliances (EUT) will be divided into 2 groups, the disturbance source appliance and the neighbor appliance groups. The disturbance source appliance is the appliance used as the disturbance source during the test and simulation, while the neighbor appliances are the appliances operated as the neighbor appliances. During simultaneous operation of appliances test, only the disturbance that is produced by the disturbance source appliance will be observed to determine the effect of neighbor appliance to the change of disturbance properties. Since the observation is only focused on the disturbances produced by the disturbance source appliances, some additional criteria of disturbance source appliance are needed as follows:

1. **Producing high disturbance**
   The disturbance source appliance is expected to produce high disturbance during the operation, so that the change of disturbance properties during the test can be measured and determined accurately.
2. **Covered in the existing standard**
   Since the study will also be used to evaluate the existing standardization, the appliance chosen as the disturbance source appliance should be covered by the existing standard.

Based on the criteria above, the household appliance that meets the disturbance source appliance criteria are induction cooker A and B. The rest of EUT will be operated as the neighbor appliances.

2.4 Disturbance Measurement and Simulation

2.3.1. Disturbance Measurement

For all testing schemes, the signal is measured in time domain using PC based differential oscilloscope picoscope 3425. The scope has 12-bit resolution and 5 MHz bandwidth [22]. The measurement characteristics can be summarized as follows

- The disturbance measurement is performed for differential mode of conducted disturbance in the frequency range 9 kHz to 150 kHz.
- A decoupling network is installed in between mains network and equipment under test. This device is used to block the noise originating from the network side entering the EUT and vice versa. Besides, the high impedance of decoupling network at disturbance frequency is also necessary to minimize the disturbance drop in the internal impedance of EUT.
- Low pass filter is used to prevent aliasing. Besides, high pass filter is also used to get better disturbance resolution by attenuating the signal below 9 kHz (especially power line fundamental frequency signal).
- The current signal is measured using current probe Tektronix P6022 which has bandwidth range within 8.5 kHz – 100 MHz for the ratio of 1 mA/mV at maximum nominal current of 6 A. Since some of EUT has nominal current higher than 6 A, an additional current transformer with the turn ratio of 1:10 has been built and used (frequency range 1 kHz – 10 MHz).

- The sampling rate used in the measurement is 1.6 µs, hence the frequency sampling is 625 kHz. Referring to the Nyquist theorem, the maximum frequency that can be obtained is 312.5 kHz. Since the study is only focused on disturbance produced by induction cooker A and B which have disturbance frequency in range 20 kHz to 25 kHz, then the sampling rate used for the measurement is sufficient.

Regarding to the sampling signal taken, the standard IEC 61000-4-7 [23] recommends that the time domain signal measurement for frequency below 2 kHz should be taken in 10 cycles of power line signal (200 milliseconds). Even though there is no standard regulating the cycles of time domain signal that should be taken for the frequency range 9 kHz to 150 kHz, the measurement will adopt the recommendation of that standard for taking 10 cycles of power line signal. For analyzing purposes, the time domain signal will be converted further to the frequency domain using Fast Fourier Transform principle in the MATLAB program [24].

Using Fourier transform, the signal can be decomposed into a sum of cosines and sines of multiple frequency as shown in equation below,

$$f(t) = x_{\mathrm{o}} + \sum_{n=1}^{\infty}\left(x_{\mathrm{n}}\cos(2\pi nt) + y_{\mathrm{n}}\sin(2\pi nt)\right) \tag{2.1}$$

where,
x_{o} = DC offset value
x_{n} = Real component value on n frequency
y_{n} = Imaginary component value on n frequency
n = Signal Frequency

For 200 ms time domain signal, the frequency bandwidth obtained from the Fourier calculation is 5Hz. Supposed there is any signal in time domain $f(t)$ for time interval of 0 < t < 0.2 s. The coefficient x_n can be obtained by multiplying the equation 2.1 with $\cos(2\pi mt)dt$ in both side and integrated for interval time 0 < t < 0.2 s.

$$\int_0^{0.2s} f(t)\cos(2\pi mt)dt = \int_0^{0.2s}\left(x_{\mathrm{o}} + \sum_{\mathrm{n}=1}^{\infty}\left(x_{\mathrm{n}}\cos(2\pi 5nt) + y_{\mathrm{n}}\sin(2\pi 5nt)\right)\right)\cos(2\pi mt)dt\,. \tag{2.2}$$

where,
x_{o} = DC offset value
x_{n} = Real component value at frequency of 5n
y_{n} = Imaginer component value at frequency of 5n
$5n$ = Multiples frequency of 5 Hz (5n)
m = Multiples frequency of 5 Hz

when $m \neq 5n$,

$$\int_0^{0.2s}\cos(2\pi 5nt)\cos(2\pi mt)dt = 0 \tag{2.3}$$

$$\int_0^{0.2s}\sin(2\pi 5nt)\cos(2\pi mt)dt = 0 \tag{2.4}$$

while when m=5n,

$$\int_0^{0.2s} \sin(2\pi 5nt)\cos(2\pi mt)dt = 0 \quad (2.5)$$

$$\int_0^{0.2s} \cos(2\pi 5nt)\cos(2\pi mt)dt = {}^1\!/_2 \quad (2.6)$$

then the coefficient of x_n can be obtained when m=5n as follows,

$$\int_0^{0.2s} f(t)\cos(2\pi mt)dt = {}^{x_\mathrm{n}}\!/_2 \quad (2.7)$$

The coefficient y_n can be obtained by multiplying the equation 2.1 with $\sin(2\pi mt)dt$ in both side and integrated for interval time 0 < t < 0.2s.

$$\int_0^{0.2s} f(t)\sin(2\pi mt)dt = \int_0^{0.2s}\left(x_\mathrm{o} + \sum_{n=1}^{\infty}\left(x_\mathrm{n}\cos(2\pi 5nt) + y_\mathrm{n}\sin(2\pi 5nt)\right)\right)\sin(2\pi mt)dt\,. \quad (2.8)$$

when the m=5n, the coefficient of y_n can be calculated as follows,

$$\int_0^{0.2s} f(t)\sin(2\pi mt)dt = {}^{y_\mathrm{n}}\!/_2 \quad (2.9)$$

The coefficient x_o can be obtained by integrating the equation 2.1 for interval time 0 < t < 0.2 s.

$$\int_0^{0.2s} f(t)dt = x_\mathrm{o} \quad (2.10)$$

The frequency bandwidth obtained from the measurement (200 ms time domain signal) is 5 Hz. Complying to the EN 50016-1-1 [25] which uses 200 Hz of bandwidth for the frequency range 9 kHz to 150 kHz, the 5 Hz frequency bandwidth then will be grouped into 200 Hz bandwidth using the equation below [1],

$$C_\mathrm{G} = \sqrt{\sum_{\mathrm{n=G-95\ Hz}}^{\mathrm{G+100\ Hz}} {C_\mathrm{n}}^2} \quad (2.11)$$

where,

C_G = Frequency component value in 200Hz bandwidth

$C_\mathrm{n} = \sqrt{{x_\mathrm{n}}^2 + {y_\mathrm{n}}^2}$ = Frequency component value in 5Hz bandwidth

G = Frequency per 100Hz

n = Frequency per 5Hz

2.3.2. Disturbance Simulation Setup

The simulation is intended to observe the disturbance properties and behavior when many appliances are connected simultaneously to the residential network. The appliances will be set to be randomly operated and connected to the network, hence the variation of simultaneous operation of appliances will be obtained. The appliance will be connected to the network using cables which have size variation of 1.5 mm^2, 2.5 mm^2 and 4 mm^2, and length variation within 0-

20 meter. The residential networks impedance used in the simulation are 5 residential networks which are measured at low (day time) and peak (night time) load periods.

To perform the simulation, three configurations should be defined. The first is the equivalent circuit of EUT and residential network. The second is random combination of connected appliances and the third is cable length variation used to connect the appliance to the network.

The simulation will be run using LTspice software. The equivalent circuit schematics and symbols for all EUT are added into the LTspice library, so that the DUT can be easily chosen and used directly from the LTSpice library when performing the simulation. For each simulation scheme, 1000 random configurations of participating appliance and cable length will be taken as the sample representing the variation of configuration. The simulation scheme properties are explained in the following subsection.

A. Constructing the equivalent circuit of appliances

The equivalent circuit of appliance contains two main parameters, the disturbance properties and the internal impedance of the appliance. The disturbance properties parameter is obtained from the measurement of disturbance produced by individual operation of appliance. The measurement scheme and the disturbance properties of appliance can be seen in Chapter 3. The internal impedance characteristics of appliances are obtained from the measurement of internal impedance. The measurement scheme and the equivalent parameters of internal impedance of appliance can be seen in Chapter 4.

The impedance equivalent circuit of appliances and mains network may contain complex combination of RLC components. The RLC components may be connected in series and parallel in the circuit which may be causing the series and parallel resonances for certain frequency range. To construct the impedance equivalent circuit from the impedance properties obtained from the measurement, the series and parallel resonance principle should be applied.

The resonance is a condition in RLC circuit in which the capacitive and inductive reactance are equal in magnitude, thereby resulting in a purely resistive impedance [26]. There are two types of resonance circuit, series and parallel resonances.

The series resonance circuit can be seen in Figure 2.5.

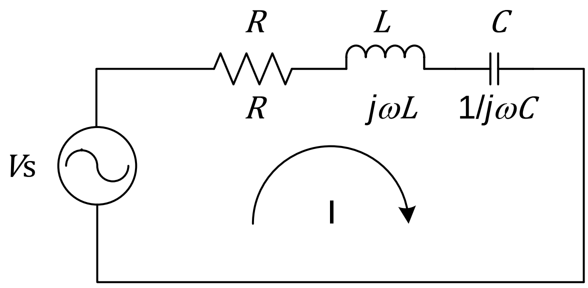


Figure 2.5. Series Resonance circuit.

$V_s = V_m \cos(\omega t)$

The impedance (Z) is

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{2.12}$$

hence, the impedance magnitude is

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \tag{2.13}$$

The resonance occurs when the capacitive and inductive reactance are equal in amplitude

$$\left(\omega L - \frac{1}{\omega C}\right) = 0 \tag{2.14}$$

This condition occurs only in the resonance frequency, so that

$$\omega_o L = \frac{1}{\omega_o C} \quad , \quad \omega_o = \frac{1}{\sqrt{LC}} \tag{2.15}$$

Since $\omega_o = 2\pi f_o$, the resonance frequency (f_o) is

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{2.16}$$

The current flowing to the circuit is

$$I = \frac{V_m}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \tag{2.17}$$

The maximum power occurred in resonance frequency is

$$P_m = \frac{1}{2}\frac{{V_m}^2}{R} \tag{2.18}$$

At certain frequency $= \omega_1,\ \omega_2$, the dissipated power is half the maximum value. It happens when the amplitude of the current is equal to $1/\sqrt{2}$ maximum current. Since the maximum current occurred at frequency resonance is $I_m = V_m/R$, then the half-dissipated power frequency is

$$\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} = R\sqrt{2} \quad , hence \quad \omega L - \frac{1}{\omega C} = R \tag{2.19}$$

so that,

$$\omega_{1,2} = \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}} \pm \frac{R}{2L} \tag{2.20}$$

The height of the curve depends on the R value while the width of the curve depends on the differences between two half power frequencies values, which is defined as Bandwidth (B).

$$B = \omega_1 - \omega_2 = \frac{R}{L} \tag{2.21}$$

Another type of resonance is the parallel resonance. The circuit can be seen in Figure 2.6.

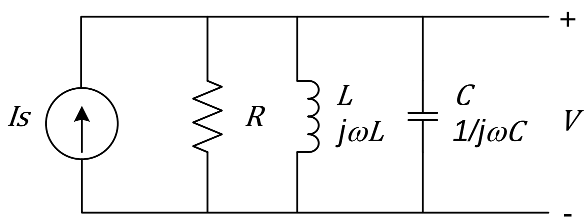


Figure 2.6. Parallel resonance circuit.

$V_s = V_m cos(\omega t)$

The admittance (Y) is

$$Y = \frac{1}{R} + j\left(\omega C - \frac{1}{\omega L}\right) \tag{2.22}$$

The voltage across the circuit is

$$V = \frac{I_m}{\sqrt{\frac{1}{R^2} + \left(\omega C - \frac{1}{\omega L}\right)^2}} \tag{2.23}$$

The resonance frequency is

$$\omega_o = \frac{1}{\sqrt{LC}} \text{ , } hence \ f_o = \frac{1}{2\pi\sqrt{LC}} \tag{2.24}$$

The half-dissipated power frequency is

$$\omega_{1,2} = \sqrt{\left(\frac{1}{2RC}\right)^2 + \frac{1}{LC}} \pm \frac{1}{2RC} \tag{2.25}$$

The bandwidth is

$$B = \omega_1 - \omega_2 = \frac{1}{RC} \tag{2.26}$$

Referring to the concept of series and parallel resonance, the impedance equivalent circuit can be constructed from the given impedance value. Figure 2.7 shows the example of impedance over frequency properties for parallel resonance circuit.

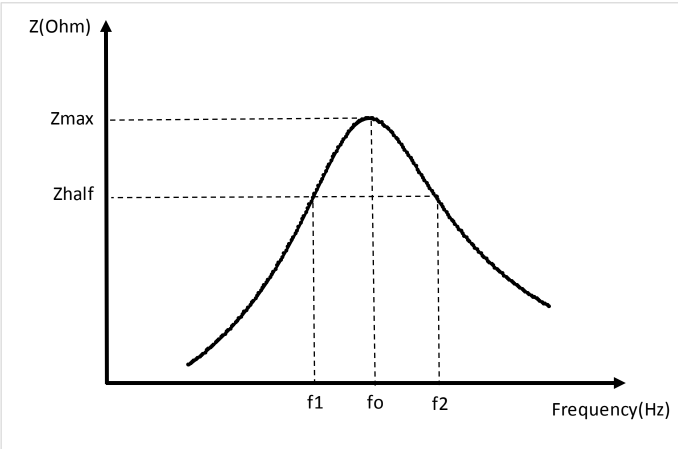


Figure. 2.7 The impedance properties of parallel resonance circuit

The steps used to construct the impedance equivalent circuit containing parallel resonance circuit are as follows,

1. Defining the resonance frequency, fo
2. Determining the maximum impedance value (Z_{max}) at resonance frequency. At resonance frequency, the Z_{max} is the resistance component ($Z_{max}=R$)
3. Calculating the impedance at half power (Z_{half}) = $Z_{max}/\sqrt{2}$
4. Finding the frequencies in half power f_1 and f_2
5. Using half power frequency values,
   calculate ω_1 and ω_2 using the equation $\omega_1 = 2 * \pi * f_1$
6. Determining the bandwidth range $B = \omega_2 - \omega_1$
7. Finding the capacitance coefficient, since $B = \frac{1}{RC}$, then $C = \frac{1}{R*B}$
8. Calculating the capacitive reactance value of $Xc = \frac{1}{\omega C}$
9. Finding the reactance at resonance frequency, $X_C = X_L$, $L = \frac{X_L}{\omega}$
10. The RLC values of parallel resonance circuit can be determined

Due to the combination of some series and parallel resonance circuits, the frequency of resonance could be shifted lower or higher. Some adjustments are needed to get better impedance equivalent circuit. LTspice program is used in adjusting the impedance equivalent parameters. An example of impedance equivalent circuit and the symbol of standby mode inverter microwave can be seen in Figure 2.8. The comparison of internal impedance properties between measurement and equivalent circuit is shown Figure 2.9. The calculation steps in finding the impedance equivalent circuit are explained in chapter 4.

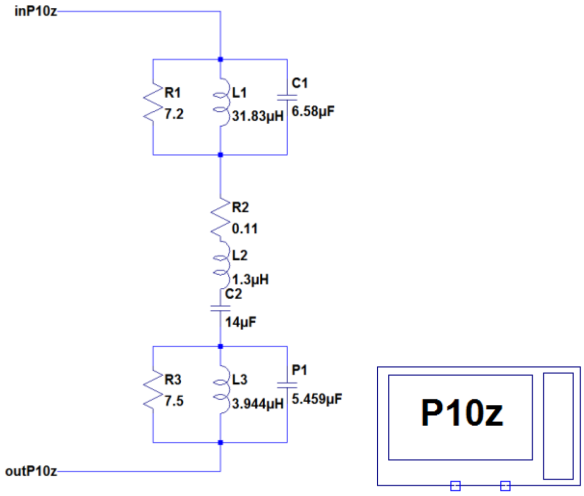


Figure. 2.8 The impedance equivalent circuit and symbol of inverter microwave

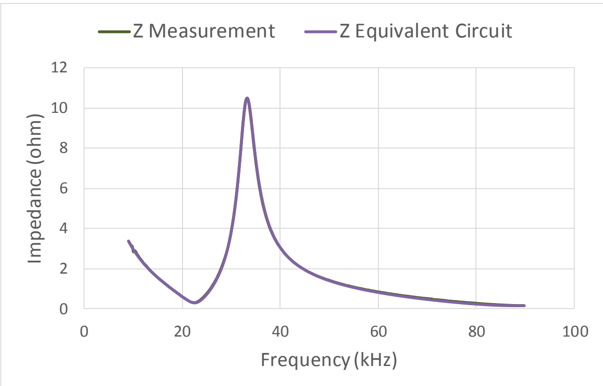


Figure. 2.9 The impedance comparison of standby mode inverter microwave

Cable length configuration

In the simulation, the appliances are planned to be connected to the network using cable. The cable sizes used are 1.5 mm^2, 2.5 mm^2 and 4 mm^2 while the cable length for each appliance is set from 0-20 meter. Since the cable length is relatively short, only resistance and inductance properties are counted. The simulation will be performed for 1000 different configurations of cable length using a random function.

For the simultaneous operation of appliances, the different random of cable length configuration for each appliance are needed. This is achieved by applying different initial random coefficient for each cable connected to appliance [27,28]. Hence, if they are 20 participating appliances in the simulation, then 20 cable lengths with different initial random coefficient should be made. The LTspice command to simulate random configuration of cable length is

$$\{c * (1 + a * (\mathrm{rand}(x + b) - 0.5))\} \tag{2.27}$$

where,

c= resistance/reactance impedance coefficient;

rand(x)=random number between 0 and 1 depending on the integer value of x.

a=coefficient to set % variation value

b= initial random coefficient

The schematic of cable length variation and the symbol can be seen in Figure2.10

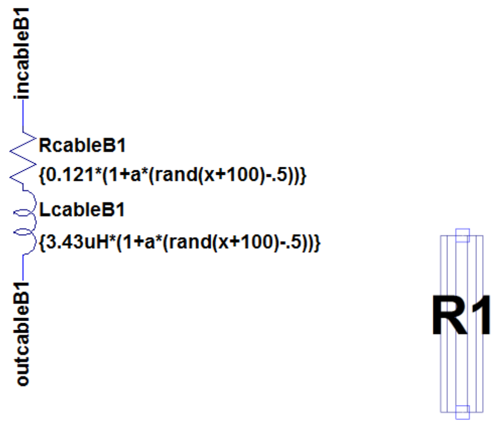


Figure. 2.10 The cable length random schematic and symbol

B. Random combination of participated appliances

The simulation will be performed by operating the appliances randomly. To realize the schemes, the voltage controlled switches are used in every appliance to manage the connection of appliances to the network. The switches are open and closed controlled by a voltage source connected to the switch control terminal. Each appliance will be connected to the certain switch which has specific random coefficient, so that the random combination of appliance can be obtained. The schematic of voltage controlled switches and the symbol can be seen in Figure 2.11.

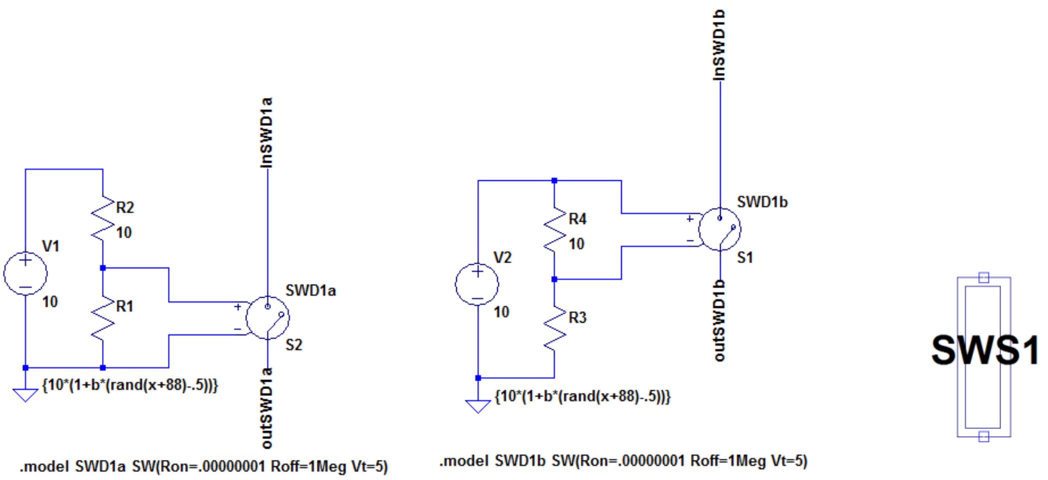


Figure. 2.11 The schematic of voltage controlled switch and symbol

The simulations are performed by connecting the appliances to the mains network through the cable and switch as can be seen in Fig 2.12. For each simulation, 1000 random configurations will be run, hence 1000 possible disturbance are obtained. The data are further processed in Excel to get the disturbance level and the distribution curve of disturbance for analysis purposes.

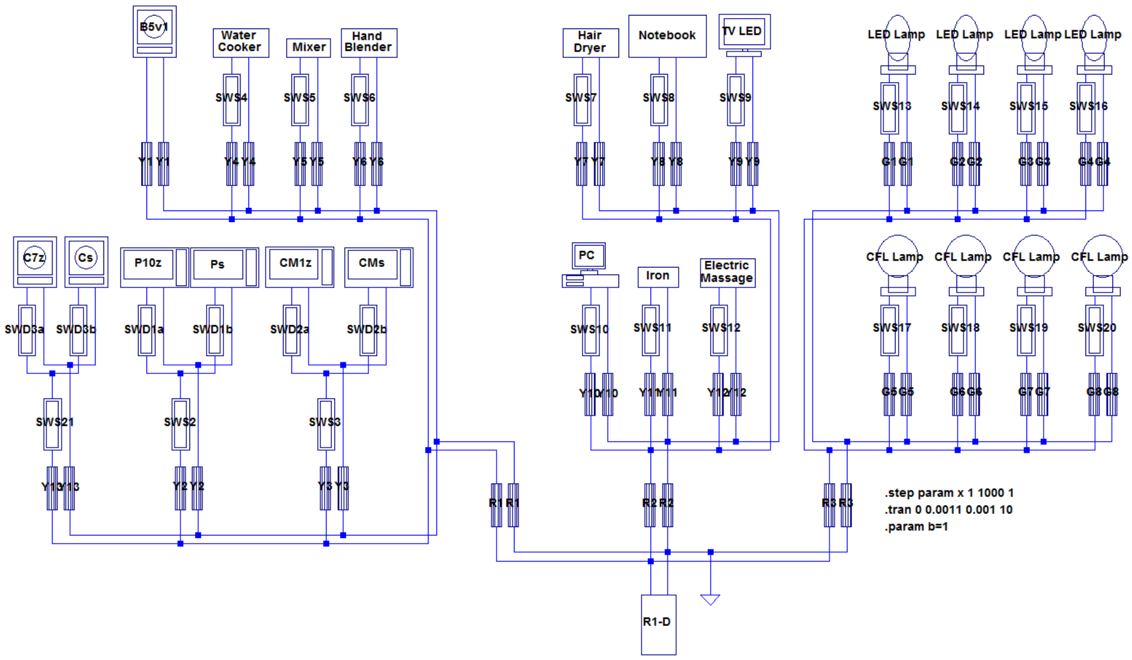


Figure. 2.12 The example of simulation circuit schematic

CHAPTER 3
DISTURBANCE PROPERTIES OF INDIVIDUAL OPERATION OF APPLIANCES

This section is focused on observing the disturbance properties and behavior of appliance in the frequency range 9 kHz to 150 kHz when it is operated individually. The disturbance of each appliance has specific level and frequency properties. The level and frequency of disturbance are depending on internal and external factors. The internal factors are generally related to the electrical circuit and working principle of appliances, while the external factors are related to the surrounding characteristics including the mains voltage level. The observation of emission will be focused on the external factor by adjusting the mains voltage level supplied to the appliance. The discussion will be divided into 2 sub sections; the disturbance level and frequency properties.

3.1. Measurement Setup

The measurement of disturbance properties of individual operation of appliance aims to obtain the actual disturbance produced by each EUT when different supply voltage levels are applied. The actual disturbance produced by the appliance cannot be measured directly from the power plugs due to the possibility of disturbance currents flowing to the grid and producing a disturbance voltage drop in the internal impedance of appliance. The method to measure the actual disturbance is by limiting the disturbance current flowing from the appliance using a decoupling network (which has high impedance at disturbance frequency) installed in between mains network and appliance (EUT). The decoupling network is also used to block the disturbance originating from the mains network entering the EUT side, so that the disturbance measured during the test is only originated from the EUT.

The voltage level that is provided at residential power outlet may not be constant over the time. EN 50160 [16] defines requirements for mains supply voltage variation tolerance delivered to the power outlet. The variation tolerance is limited to ±10% of the nominal voltage rating. The voltage level variation may influence the disturbance generated by the appliances. To observe the effect of mains voltage level to the disturbance, the tests are performed by varying the supply voltage level applied to the appliances from 239 V to 206 V with the step voltage of 3 V. There are 12 steps of mains voltage level 239 V, 236 V, 233 V, 230 V, 227 V, 224 V, 221 V, 218 V, 215 V, 212 V, 209 V, and 206 V. The voltage level is adjusted and kept constant during the test by controlling the autotransformer. For each supply voltage level, 50 samples are taken. The average value of 10 highest disturbances will be taken as the disturbance level of each appliance. The schematic of testing diagram is shown in Figure 3.1.

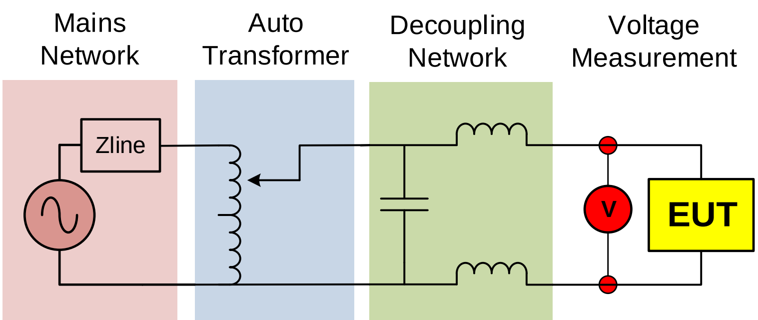


Figure 3.1. The schematic diagram of the testing of disturbance properties at different mains voltage level.

3.2. Disturbance Level Characteristics

A. Induction Cooker A

The measurement is performed when the induction cooker A is operated at the 5th power level option which was found to generate the highest emissions. The disturbance frequency spectrum generated by the induction cooker A for frequency range 9 kHz to 150 kHz is shown in Figure 3.2. Referring to the spectrum, it can be noticed that the induction cooker A has main disturbance in the frequency range within 21-24 kHz. When the mains voltage levels are varied, the disturbances generated by the induction cooker A are also changed. Figure 3.3 shows the mains disturbance frequency spectrum of induction cooker A when the mains supply voltage levels are varied from 239 V to 206 V. From the curve, it can be noticed that for induction cooker A, the mains supply voltage level influences the disturbance level and frequency.

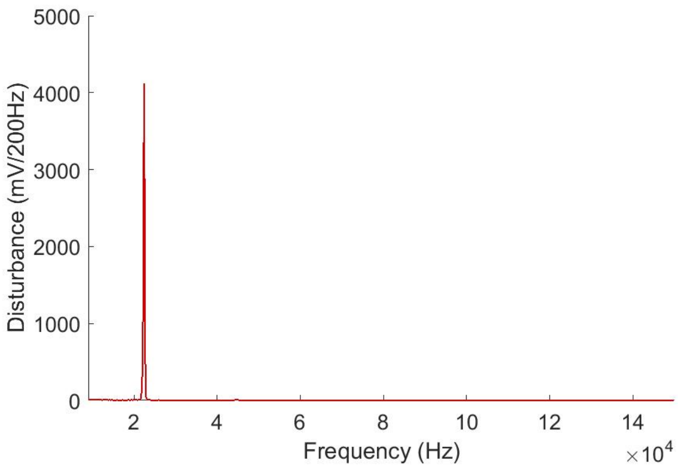


Figure 3.2 The disturbance frequency spectrum of induction cooker A for frequency range of 9-150 kHz.

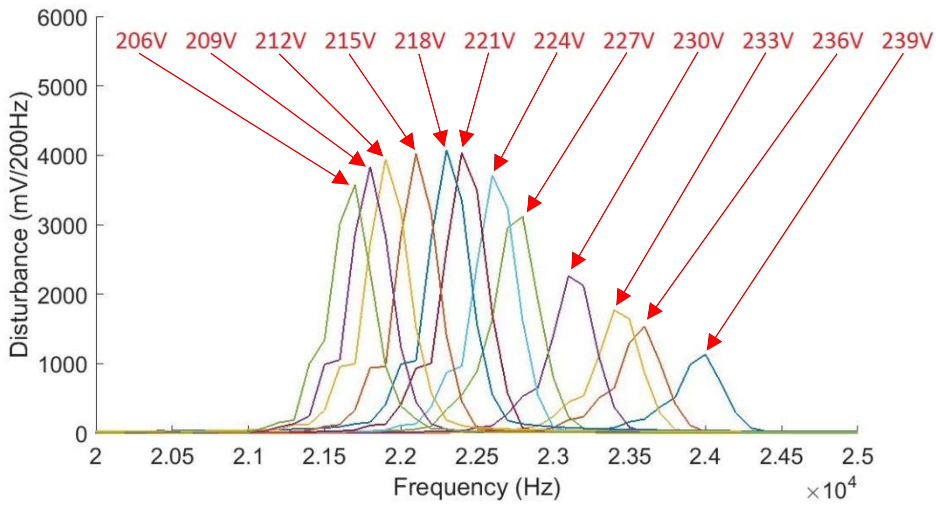


Figure 3.3 The main disturbance of induction cooker A when varied mains voltage level is applied.

Figure 3.4 shows the of relationship between the mains voltage level and the disturbance produced by induction cooker A. It is clear from the curve that for mains voltage range 239 V – 206 V, getting down the mains voltage from 239 V to 218 V will cause the disturbance level greater. But then after 218 V, getting down the mains voltage to 206 V will cause the reduction of disturbance level emitted by induction cooker A. The lowest disturbance level of 1120 mV is occurred at mains voltage of 239 V, while the highest disturbance level of 4151 mV is occurred at mains voltage level of 218 V. The differences between the lowest and highest disturbance level of induction cooker A for mains voltage variation from 239 V to 206 V is very significant and reaches 270 % (comparing to the lowest disturbance).

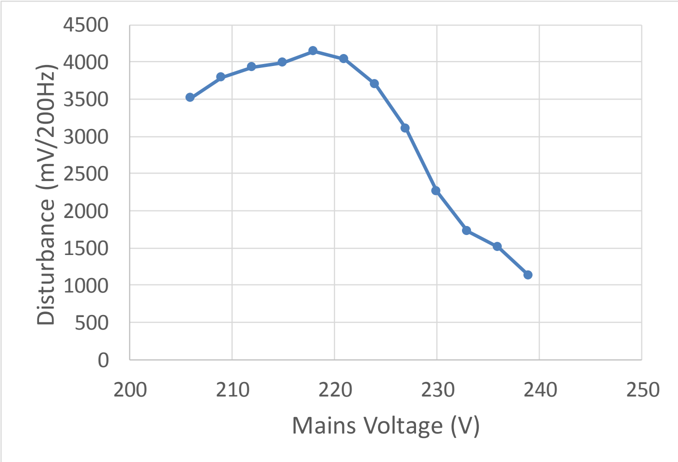


Figure 3.4 The relationship between the disturbance of induction cooker A and mains voltage level

Induction Cooker B

The observation of emission of induction cooker B is performed for the 7th power level operation option which was found to produce the highest emission level. The emission frequency spectrum generated by the induction cooker B for frequency range within 9-150 kHz is shown in Figure 3.5. Referring to the spectrum, it can be noticed that the induction cooker B generates the main emission also in frequency range within 21-24 kHz. Figure 3.6 shows the disturbance voltage emitted by induction cooker B when the mains supply voltage is varied from 239 V to 206 V. According to the curve, it can be noticed that the mains supply voltage level affects the disturbance produced by induction cooker B. Figure 3.7 shows better visualization of relationship between mains voltage and disturbance level for induction cooker B. It is clear from the curve that for mains voltage range 239 V to 206 V, getting down the mains voltage will cause higher emission. The emission level is increased from 153 mV to 282 mV when the mains voltage is decreased from 239 V to 206 V. The difference of the highest and lowest emission level of induction cooker B reaches 84 %.

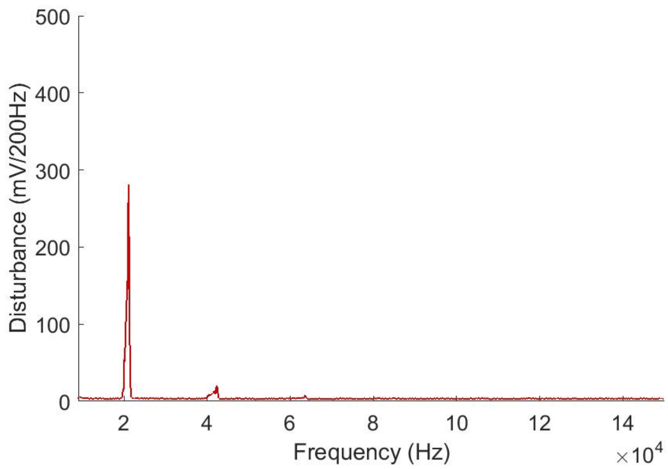


Figure 3.5 The emission frequency spectrum of induction cooker B for frequency range of 9-150 kHz.

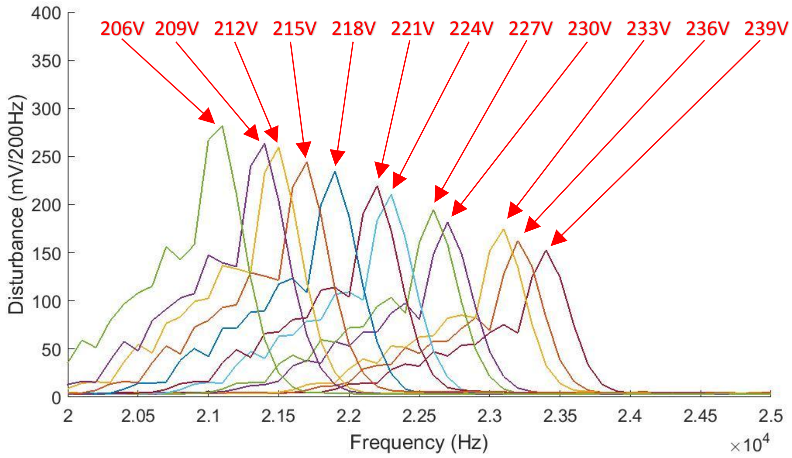


Figure 3.6 The mains disturbance of induction cooker B for varied mains voltage level from 206 V-230 V

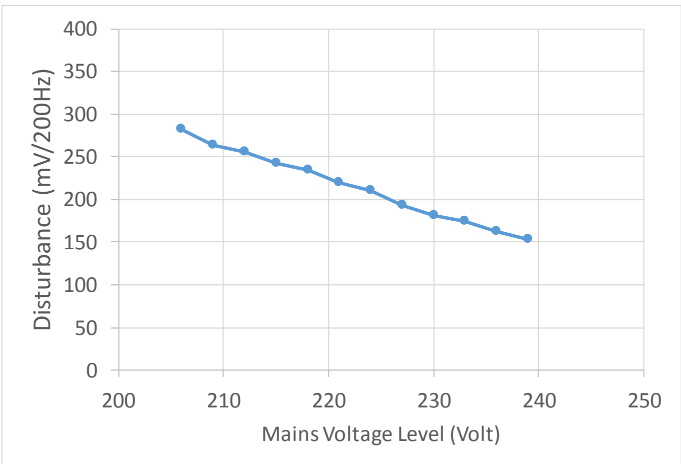
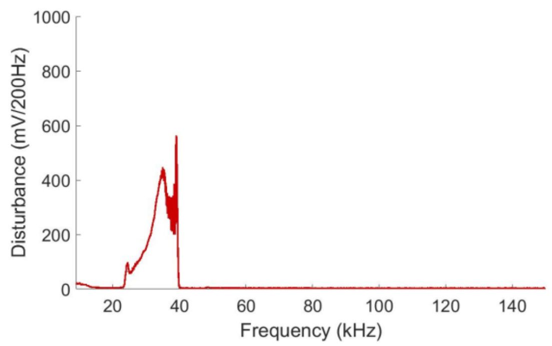
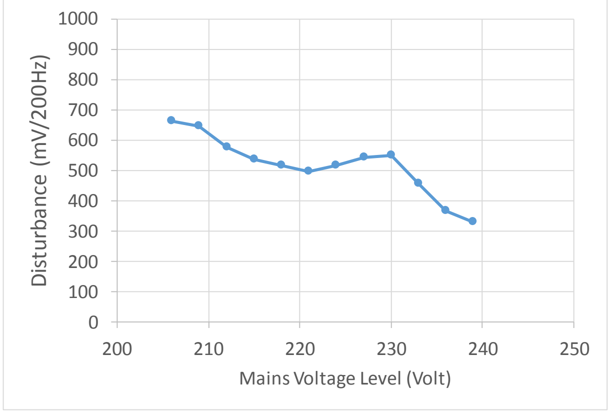
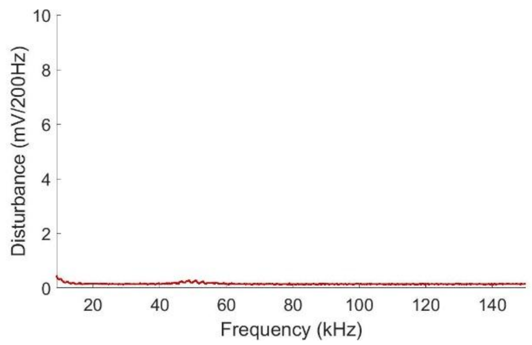
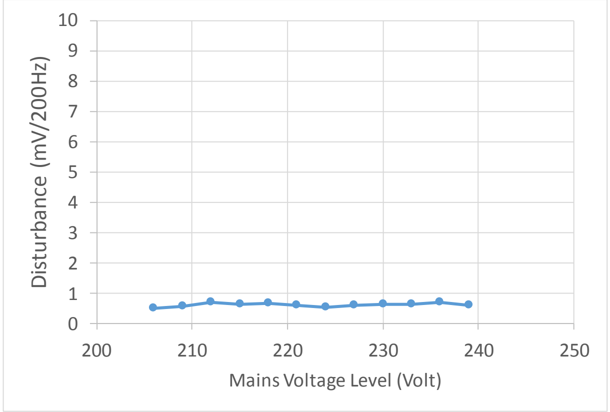


Figure 3.7 The relationship between the disturbance of induction cooker B and mains voltage level

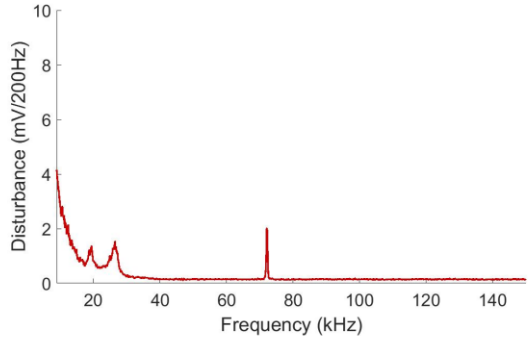
The disturbance characteristics of other appliances

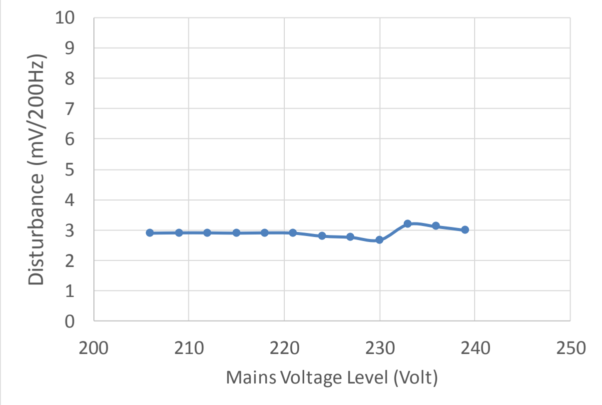
The disturbance frequency spectrum in the frequency range 9 kHz to 150 kHz for the rest of EUT can be seen in Table 3.1. The highest emission levels of each appliance for varied mains supply voltage from 239 V to 206 V are also shown in Table 3.1. According to the spectrum, it can be noticed that the emission of each appliance has different level and frequency.

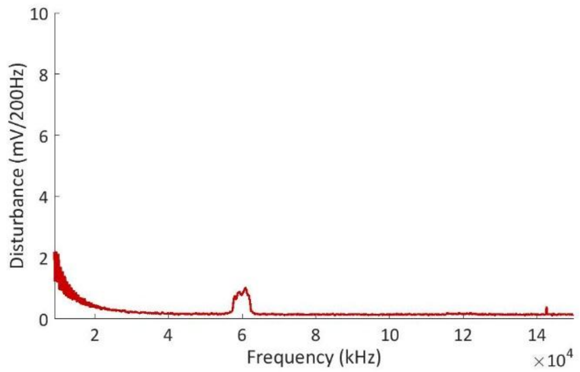
Table 3.1 The disturbance frequency spectrum and the disturbance properties of appliances

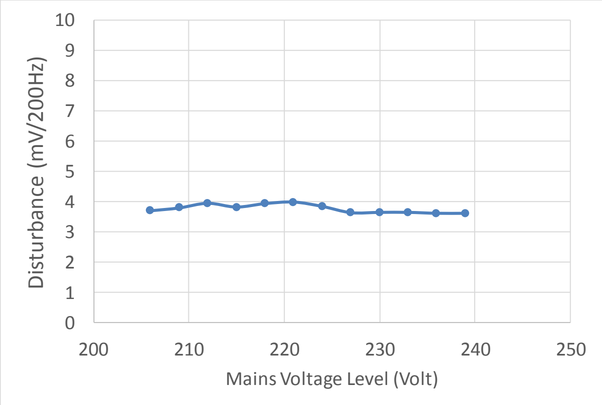
Appliance	Description	Disturbance Properties
Inverter Microwave Oven	**Disturbance Frequency Spectrum 9 kHz to 150 kHz** The emission of inverter microwave has broadband frequency within 24 kHz to 40 kHz range. The highest emission level is occurred at frequency around 38-39 kHz.	
	Disturbance vs Mains Voltage Mains voltage level affects the emission of inverter microwave. The highest emission of 662 mV is occurred at mains voltage of 206 V while the lowest emission of 330 mV is occurred at mains voltage of 239 V.	
Conventional Microwave Oven	**Disturbance Frequency Spectrum 9 kHz to 150 kHz** There is almost no disturbance produced by conventional microwave oven in the frequency range within 9-150 kHz.	
	Disturbance vs Mains Voltage Properties Refer to Figure, it can be noticed that the emission of conventional microwave is constant.	

<table>
<tr>
<td rowspan="2">Personal Computer</td>
<td>Disturbance Frequency Spectrum 9 kHz to 150 kHz

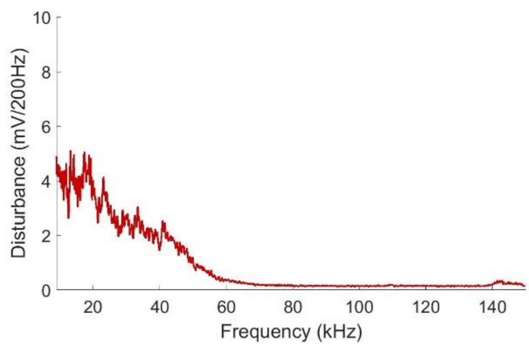
The emissions of personal computer are in frequency ranges of 9-30 kHz and frequency 72 kHz. The effect of mains voltage level is only observed for the disturbance at frequency 72 kHz</td>
<td>
</td>
</tr>
<tr>
<td>Disturbance vs Mains Voltage Properties

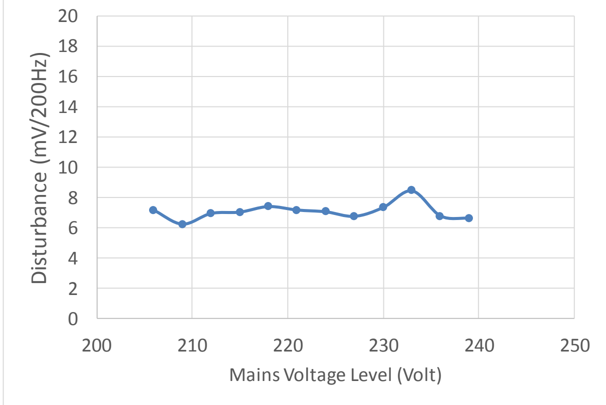
Generally, the emission level of personal computer is lower at higher mains voltage level.</td>
<td>
</td>
</tr>
<tr>
<td rowspan="2">LED Television Set</td>
<td>Disturbance Frequency Spectrum 9 kHz to 150 kHz

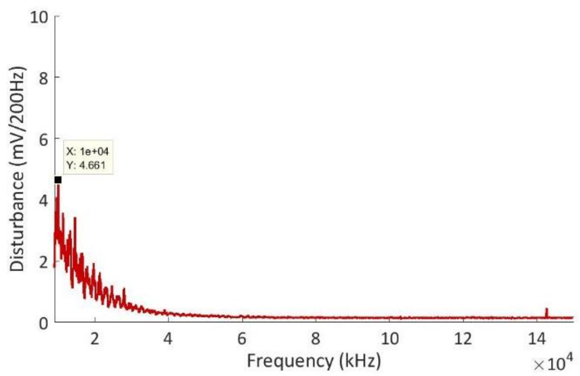
The emission of the television set is in frequency ranges of 9-20 kHz and 58-62 kHz. The mains voltage level influence is only observed for the disturbance in the frequency range within 58 – 62 kHz</td>
<td>
</td>
</tr>
<tr>
<td>Disturbance vs Mains Voltage Properties

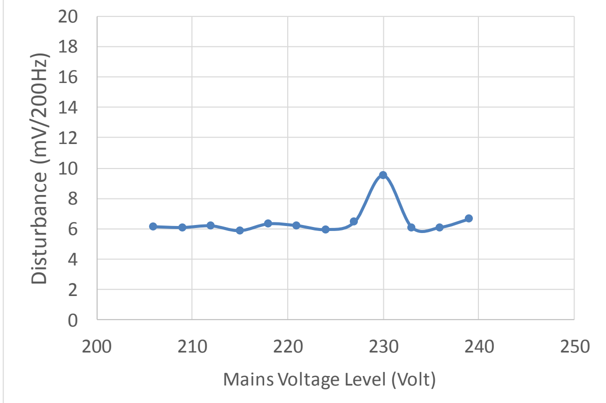
The emission level of TV LED is 26 mV and almost constant for all mains voltage level.</td>
<td>
</td>
</tr>
</table>

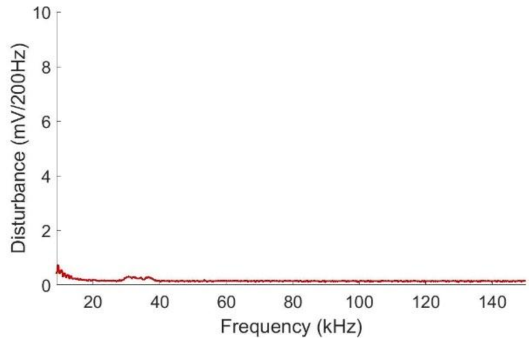
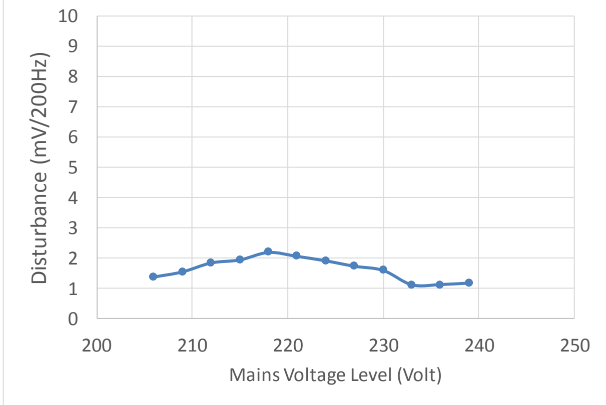
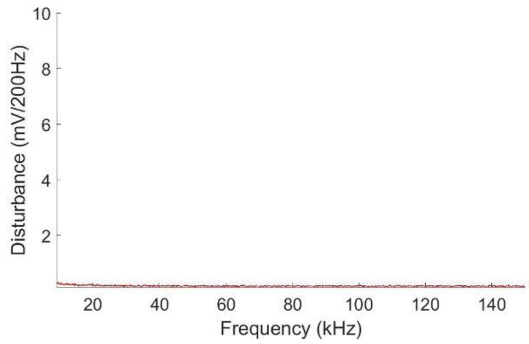
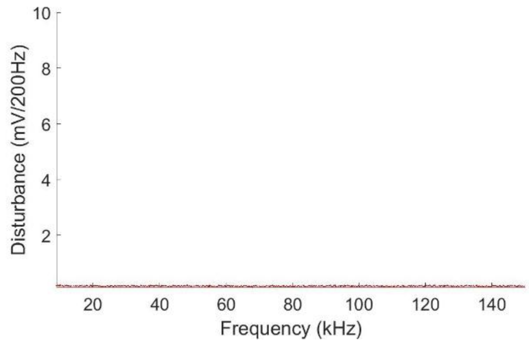
<table>
<tr>
<td rowspan="2">Notebook</td>
<td>Disturbance Frequency Spectrum 9 kHz to 150 kHz

The emission of notebook is in frequency range within 9 kHz to 60 kHz.</td>
<td></td>
</tr>
<tr>
<td>Disturbance vs Mains Voltage Properties

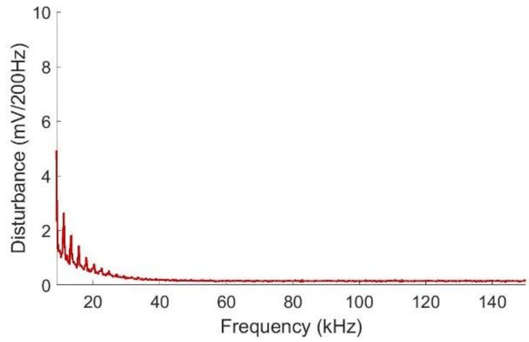
Generally, the emission of notebook is almost constant and not affected by the variation of mains voltage level.</td>
<td></td>
</tr>
<tr>
<td rowspan="2">Hairdryer</td>
<td>Disturbance Frequency Spectrum 9 kHz to 150 kHz

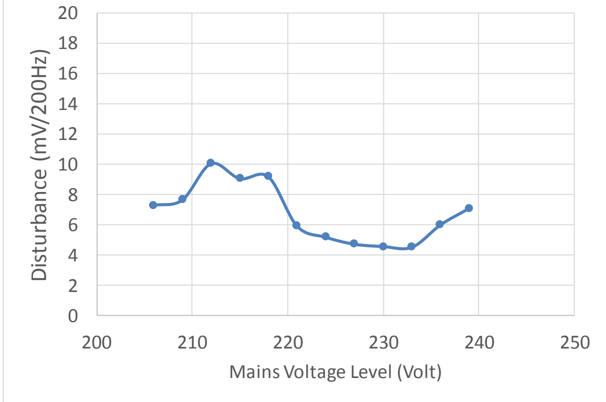
The emission of hairdryer is in the frequency range within 9 kHz to 40 kHz.</td>
<td></td>
</tr>
<tr>
<td>Disturbance vs Mains Voltage Properties

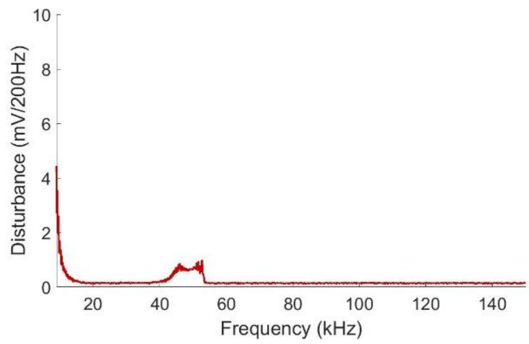
Generally, the emission of hairdryer is almost constant except at the nominal voltage level (230 V).</td>
<td></td>
</tr>
</table>

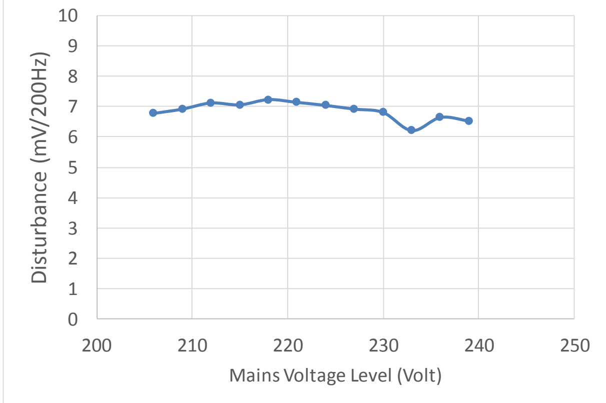
Electric Massage	**Disturbance Frequency Spectrum 9 kHz to 150 kHz** The emission of electric massage device is in the frequency around 10 kHz.	
	Disturbance vs Mains Voltage Properties Generally, the emission of electric massage is almost constant and not affected by the variation of mains voltage level.	
Water Cooker	**Disturbance Frequency Spectrum 9 kHz to 150 kHz** There is no disturbance produced by water cooker in the frequency range within 9 kHz to 150 kHz.	
Iron	**Disturbance Frequency Spectrum** There is no disturbance produced by iron in the frequency range 9 kHz to 150 kHz.	

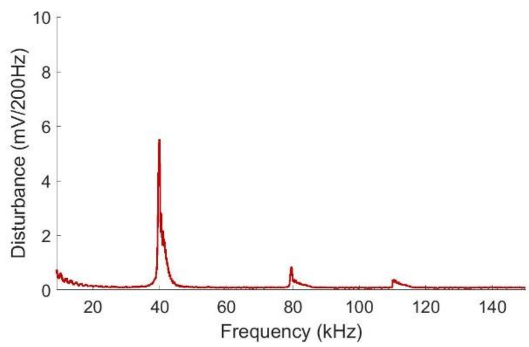
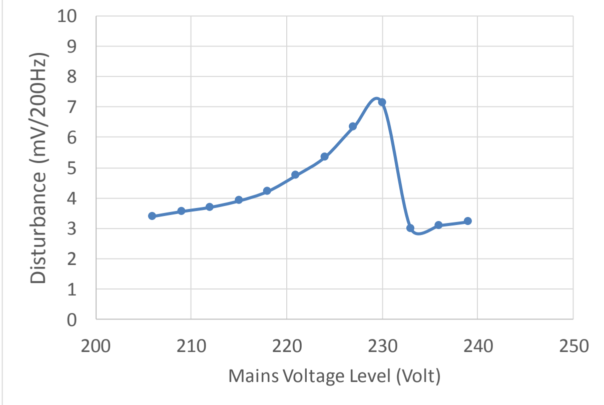
<table>
<tr>
<td rowspan="2">Mixer</td>
<td>Disturbance Frequency Spectrum 9 kHz to 150 kHz

The main disturbance produced by mixer is in the frequency range 9 kHz to 12 kHz.</td>
<td>
</td>
</tr>
<tr>
<td>Disturbance vs Mains Voltage Properties

The mains voltage level is slightly affecting the emission level of mixer.</td>
<td>
</td>
</tr>
<tr>
<td rowspan="2">LED Lamp</td>
<td>Disturbance Frequency Spectrum 9 kHz to 150 kHz

The emission of the LED is in frequency ranges of 9-15 kHz and 45-55 kHz. The mains voltage level influence is only observed for the disturbance in the frequency range within 9-15 kHz.</td>
<td>
</td>
</tr>
<tr>
<td>Disturbance vs Mains Voltage Properties

The mains voltage level is not affecting the emission level of LED lamp. The emission level is almost constant for all mains voltage level.</td>
<td>
</td>
</tr>
</table>

Compact Fluorescent Lamp	**Disturbance Frequency Spectrum 9 kHz to 150 kHz** The main disturbance produced by this compact fluorescent lamp is at the frequency around 40 kHz.	
	Disturbance vs Mains Voltage Properties The mains voltage level is affecting the emission level of CFL. The disturbance level is linearly proportional with mains voltage level in the range of 206V-230 V and relatively constant for the range 233V-239 V.	

The observation gives an overview of disturbance produced by household appliances in the frequency range 9 kHz to 150 kHz. There are 3 types of disturbance behavior of household appliance when varied mains voltage level is applied to the appliances as can be seen in Table 3.2. The first type has constant relationship between the produced disturbance and supply voltage level. The appliances classified in this type are conventional microwave, PC, television, notebook, electric massage and LED lamp. The second type has inverse relationship between the produced disturbance and the supply voltage level. The appliances classified in this type are induction cooker B. The third type has a combination of linear and inverse relationship between the produced disturbance and the supply voltage level. The disturbance is linearly proportional for specific range of the mains voltage level and it is inversely proportional for other specific range of the mains voltage level. The appliances classified in this type are induction cooker A, inverter microwave, mixer, hairdryer and CFL

Table 3.2 The type of disturbance behavior of appliances related to the mains voltage level variation

TYPE	BEHAVIOR	APPLIANCES
1	Constant	Conventional Microwave, PC, LED Lamp, LED-TV, Notebook, Electric Massage
2	Inverse	Induction Cooker B
3	Combination of Linear and Inverse	induction cooker A, Inverter Microwave, Mixer, Hairdryer, CFL

3.3. Disturbance Frequency Property

Some household appliances produce disturbance in the frequency range 9 kHz to 150 kHz during their operation. The disturbance has two main properties, level and frequency of disturbance. The frequency of disturbance is normally related to the switching frequency adopted by the appliances. Responding to the mains network properties, the switching frequency applied by appliance can be constant or adaptive depending on its output optimization. When the switching frequency used is adaptive, then the disturbance frequency generated will also change corresponding to the network properties including mains voltage level.

Each household appliance has unique internal impedance property which the value normally varies over frequency. This internal impedance is one of the main factor affecting the disturbance occurred in the network. If the disturbance frequency is shifted, the internal impedance value of appliance will also be changed corresponding to the disturbance frequency. Moreover, the shifting of disturbance frequency will also change the impedance value of mains network and neighbor appliances which are consequently affecting the disturbance occurred in the network.

In this section, the characteristics of disturbance frequency produced by the disturbance source appliances for different mains voltage level will be observed by varying the mains supply voltage level from 239 V to 209 V with the step voltage of 3 V as mentioned in section 3.1.

A. Induction Cooker A

The observation is conducted to the induction cooker A for the 5th power level option. Fig 3.8. shows the disturbance frequency produced by induction cooker A when the mains supply voltage is varied from 239 V to 206 V. From the curve, it can be noticed that the mains supply voltage level is affecting the disturbance frequency. At mains voltage 239 V, the disturbance frequency generated by induction cooker A is 24 kHz. The disturbance frequency is decreased gradually to 21.7 kHz when the mains voltage level is decreased to 206 V.

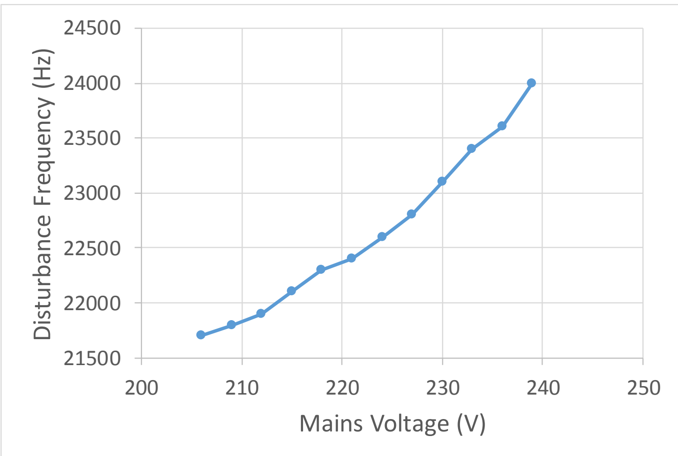


Figure 3.8 The disturbance frequency of induction cooker A for varied mains voltage level

B. Induction Cooker B

The observation is conducted to the induction cooker B for the 7th power level option. Figure 3.9 shows the disturbance frequency produced by induction cooker B when the mains supply voltage is varied from 239 V to 206 V. Referring to the curve, we can determine that the mains supply voltage level is affecting the disturbance frequency. For mains voltage 230V, the disturbance frequency generated by induction cooker B is 23.2 kHz. The disturbance frequency is gradually decreased to 21.1 kHz when the mains voltage level is decreased to 206 V.

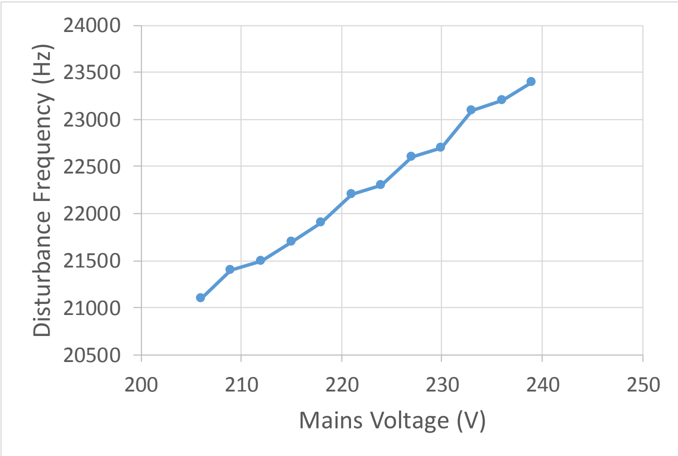


Figure 3.9 The disturbance frequency of induction cooker B for varied mains voltage level

The observation gives another behavior of disturbance produced by household appliances. For some household appliances, particularly the primary appliances, the disturbance frequency is affected by mains voltage level applied. The disturbance frequency of induction cooker A and B is almost linearly proportional with the mains voltage level.

This disturbance frequency shift behavior is important for analyzing the disturbance occurred in shared network environment when many appliances are connected and operated simultaneously. The simultaneous operation of appliances may be resulting in high current flowing and causing the significant drop voltage in the network. This drop voltage may cause disturbance frequency shift on disturbance source appliances. This disturbance frequency shift will affect the change of its internal impedance properties, neighbor impedance and mains network impedance properties which eventually affect the disturbance appeared in the network.

CHAPTER 4
INTERNAL IMPEDANCE PROPERTIES OF APPLIANCES

Every appliance has internal impedance related to their internal electrical circuit. The internal impedance of appliances may influence the disturbance occurred in the network. Hence, finding out the internal impedance of appliances is crucial for analyzing the disturbance behavior in the network. The appliances that are using inverter technology normally generate disturbances in the frequency range 9 kHz to 150 kHz. To comply with requirements of EMC product standards, which specify limits for disturbance voltages between 150 kHz to 30 MHz, some appliances are equipped with EMC filter for reducing the emission. This EMC filter has relatively low impedance for certain frequency range as intended. The interest disturbances in the study are produced by induction cooker A and B which have disturbance frequency in the range 21 kHz to 24 kHz as can be seen in Figure 3.8 and 3.9. Hence, the internal impedance properties of all participating appliances (EUT) in the frequency range 21 kHz to 24 kHz should be identified.

4.1 Measurement Scheme

The measurement of internal impedance of appliance is conducted by connecting the appliance to the mains network through coupling decoupling network (CDN). The voltage signals in the frequency range 9 kHz to 90 kHz are generated by PC based signal generator and injected to the EUT through high frequency input of CDN. The function of CDN is to block the high frequency signal generated by PC based signal generator entering the mains network side while it is injected to the EUT. The high frequency voltage and current signals at the EUT side are measured. The voltage and current time domain signal then will be converted to frequency domain. Since the voltage and current signals are measured using high pass filter and high frequency current probe respectively, the conversion ratio of high pass filter and current probe are applied to the measured value to obtain the real voltage and current signal value. The internal impedance of appliances is then calculated by dividing the voltage by the current values. The testing diagram of internal impedance measurement can be seen in fig 4.1.

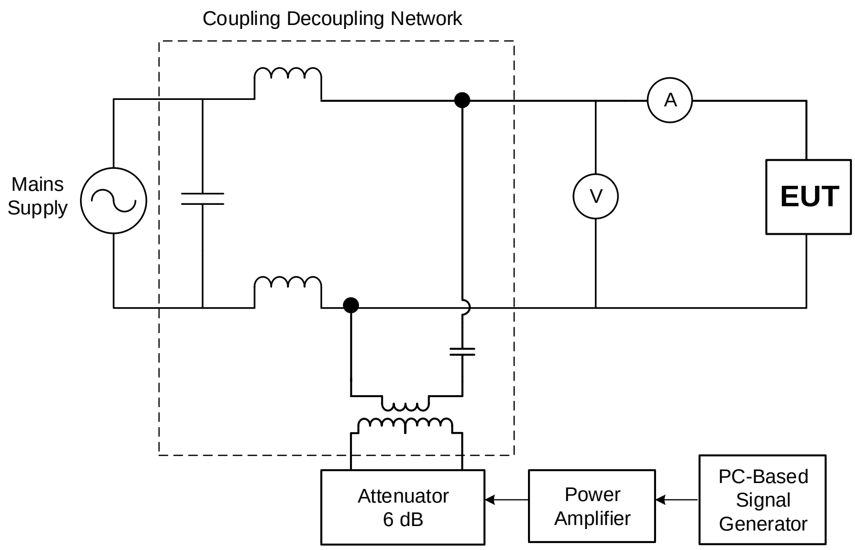


Figure 4.1 The testing scheme for measuring the internal impedance of appliance

Since the interest disturbance frequency is in the range of 21 kHz to 24 kHz (produced by induction cooker A and B), the internal impedance of appliances in frequency range 9 kHz to 90 kHz obtained in this testing will be adequate. The frequency spectrum of the voltage signal generated by the testing device at no load condition is shown in Figure 4.2 while the example of voltage and current frequency spectrums during the measurement of internal impedance of appliance are shown in Fig 4.3.

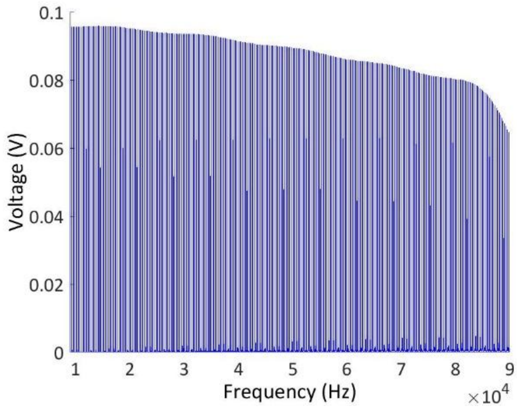


Figure 4.2. The signal frequency spectrum in Frequency range 9 kHz to 90 kHz at no load condition

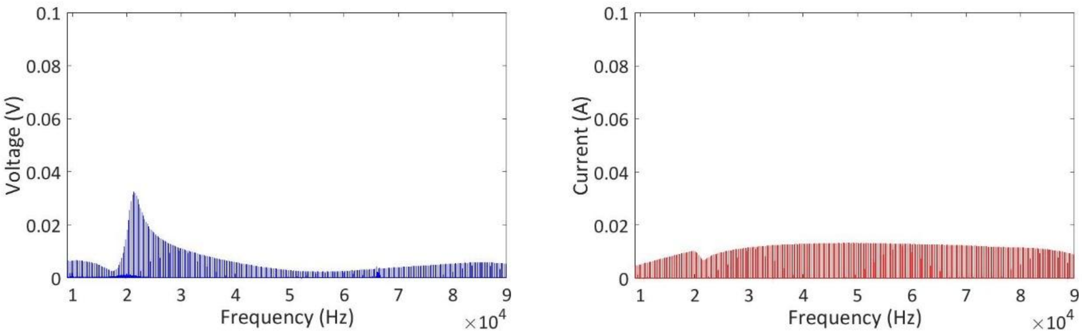


Figure 4.3. The voltage and current frequency spectrums obtained when measuring the internal impedance of induction cooker A

4.2 Internal Impedance of Appliances

A. Induction Cooker A

The induction cooker A has two mode options; standby and operation mode. For operation mode, there are 6 power level options. In this study, the internal impedance measurement are only conducted for standby mode and operation mode at the 5th power level which generates the highest disturbance.

A.1 Standby Mode Induction Cooker A

The impedance properties of standby mode of induction cooker A in the frequency range 9 kHz to 90 kHz can be seen in Figure 4.4. According to the impedance curve, it can be noticed that two series resonances appear. The first series resonance is occurred at frequency 17.5 kHz with impedance value of 0.32 Ohm while the second series resonance is occurred at frequency of 57 kHz with impedance value of 0.15 Ohm. Since the standby mode induction cooker A has very low impedance at series resonance frequencies, it becomes a good filter for any signal or disturbance on that frequency.

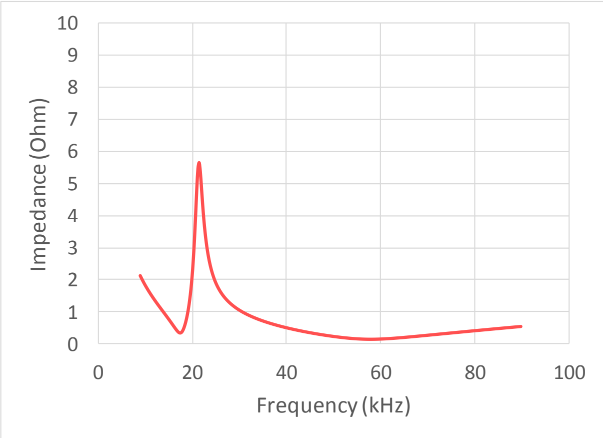


Figure 4.4 The impedance curve of standby mode induction cooker A.

To analyze the disturbance behavior when many appliances are operated simultaneously in the network, it is essential to find the impedance equivalent circuit, so that the disturbance interaction between appliances can be simulated. The impedance equivalent circuit is constructed by referring the impedance curve obtained from measurement particularly at series and parallel resonances frequencies. According to section 2.3.2.A, the impedance equivalent circuit parameter is calculated as below.

1. Calculating the capacitance of the circuit
   From the impedance curve, it can be noticed that at starting frequency of 9 kHz, the impedance has capacitive properties.
   - Sample frequency = 10050 Hz
   - Impedance at sample frequency = 1.94 Ω

   The capacitance value (C) can be found using reactance equation
   $X_C = 1/\omega C$, $C = 1/\omega X_C = 1/(2 * \pi * 10050 \text{ Hz} * 1.94 \,\Omega) = 8.16 \,\mu\text{F}$

2. Determining the capacitance and inductance at parallel resonance:
   From the impedance value at parallel resonance, some data can be calculated as below
   1. Frequency resonance: 21550 Hz
   2. $Z_{maximum}$ = 5.60 Ω
   3. $Z_{half\ power} = Z_{maximum} / \sqrt{2}$ = 3.96 Ω
   4. Frequency at half power = $f_1 = 20800 \text{ Hz}$, $f_2 = 22450 \text{ Hz}$
   5. Using half power frequency value, then $\omega_1 = 2 * \pi * f_1 = 130690 \text{ rad s}^{-1}$, $\omega_2 = 141058 \text{ rad s}^{-1}$
   6. The bandwidth range $B = \omega_2 - \omega_1 = 10367 \text{ rad s}^{-1}$
   7. Since $B = \frac{1}{\text{RC}}$, then $C = \frac{1}{\text{R}*\text{B}} = \frac{1}{5.60\,\Omega * 10367 \text{ rad s}^{-1}} = 17.22 \,\mu\text{F}$
   8. The capacitive reactance value is $X_C = \frac{1}{\omega \text{C}} = \frac{1}{2*\pi*21550 \text{ Hz} * 17.22 \,\mu\text{F}} = 0.43 \,\Omega$
   9. At frequency resonance, $X_C = X_L = 0.43 \text{ Ohm}$, $L = \frac{X_L}{\omega} = \frac{0.43\,\Omega}{2*\pi*21550 \text{ Hz}} = 3.17 \,\mu\text{H}$

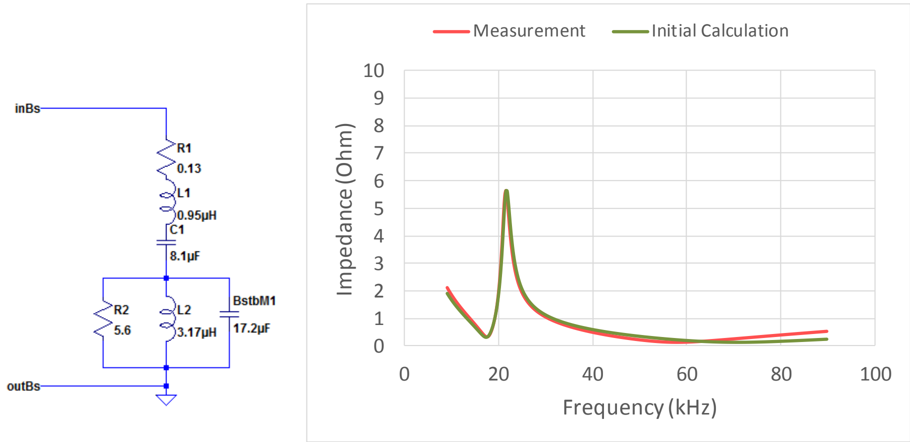
   The RLC value for this parallel resonance are:

R = 5.60 Ω
L = 3.17 µH
C = 17.22 µF

3. Calculating capacitance and inductance for the series resonance
    10. Resonance frequency = 57.05 kHz
    11. Impedance value (R): 0.13 Ω
    12. Capacitance value = 8.16 µF
    13. Capacitive Reactance $Xc = \frac{1}{\omega C} = \frac{1}{2*\pi*57050\ \text{Hz}*8.16\ \mu\text{F}} = 0.342\ \Omega$
    14. Inductive Reactance $X_L = X_C = 0.342\ \Omega$, $L = \frac{X_L}{\omega} = \frac{0.342\ \Omega}{2*\pi*57050\ \text{Hz}} = 0.95\ \mu\text{H}$

The RLC value for this series resonance are:
R = 0.13 Ω
L = 0.95 µH
C = 8.16 µF

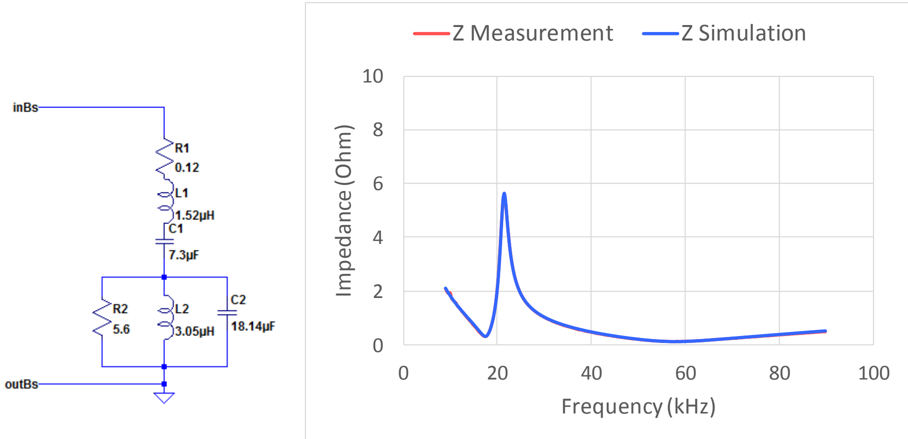
The initial impedance equivalent circuit parameter of standby mode induction cooker obtained from the initial calculation can be seen in Fig 4.5(a). The impedance curve comparison between measurement and initial calculation is shown in Fig 4.5(b). Referring to the curve, it can be noticed that there is a little difference of the impedance curve between the measurement (red line) and the calculation (green line).



(a) (b)

Figure 4.5 The impedance equivalent circuit of induction cooker A
(a) Initial equivalent circuit, (b) Impedance comparison

To obtain a better impedance equivalent impedance curve, some adjustments of impedance equivalent parameter values based on the characteristics of resistance, capacitance and inductance behavior in the circuit are taken. Every modification of impedance equivalent parameter is checked and validated using LTspice software. The final equivalent circuit parameter of standby mode induction cooker A can be seen in Fig 4.6. It can be noticed that the final impedance curve resulted from the simulation is relatively close to the impedance taken from measurement especially in the frequency range 20 kHz to 25 kHz. This internal impedance equivalent circuit then will be used further for the simulation purposes.



(a) (b)

Figure 4.6 The impedance of standby mode of induction cooker A
(a) Final equivalent circuit (b) Impedance comparison

A.2 Operation Mode Induction Cooker A

For the operation mode of induction cooker A, the impedance properties of induction cooker A in the frequency range 9 kHz to 90 kHz can be seen in Figure 4.7. According to the impedance curve, it can be noticed that there are two series resonance impedances. The first series resonance is occurred at frequency 18.5 kHz with impedance value of 0.32 Ohm while the second series resonance is occurred at frequency of 57 kHz with impedance value of 0.15 Ohm. Figure 4.7 also shows a spike impedance at frequency within 21-23 kHz. The spike impedance happens due to the disturbance signal generated by the operation mode of induction cooker A. When the disturbance has similar frequency with the voltage signal generated by the impedance measurement device, the voltage and current signal measured at that frequency will be mixed which eventually leads to an inaccurate impedance value at that frequency. To overcome this issue, the internal impedance measurement is conducted at different supply voltage levels to get some different spike frequencies (due to the different disturbance frequency produced by induction cooker A at different supply voltage levels, see Fig 3.8) so that the internal impedance of induction cooker A can be determined.

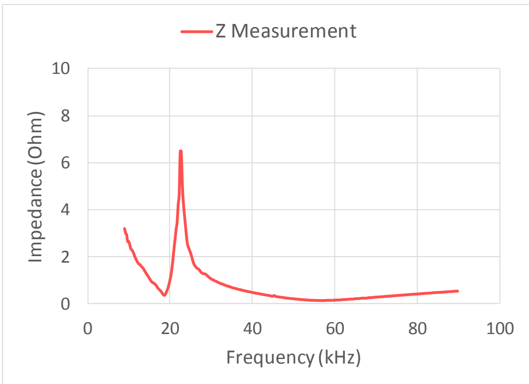
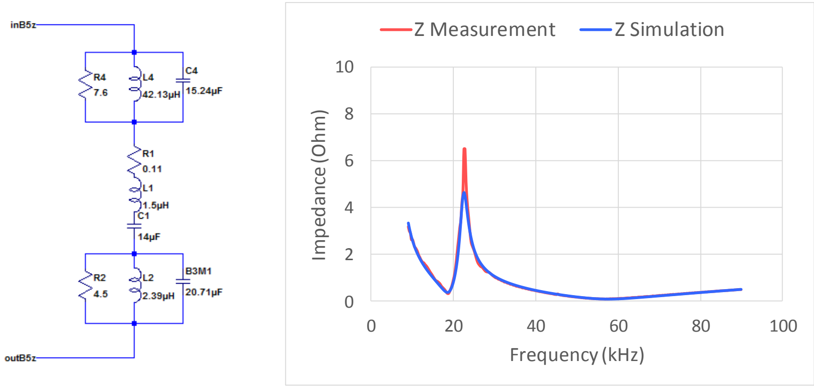


Figure 4.7 The impedance curve of operation mode induction cooker A

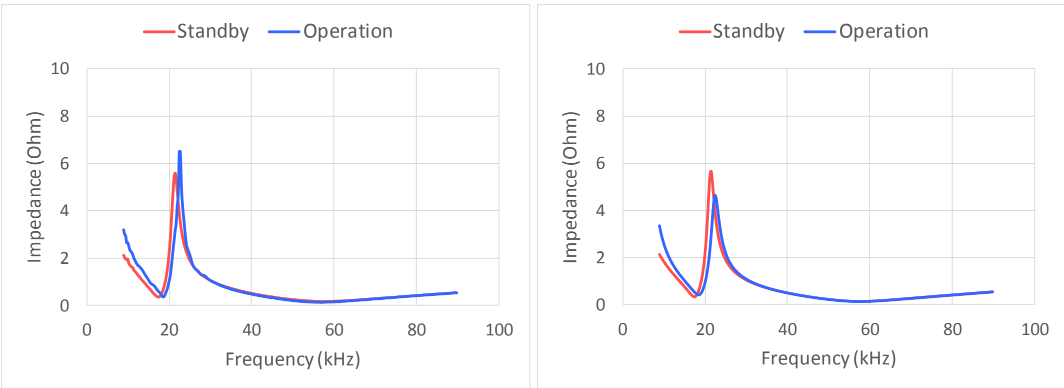
Using similar calculation method as done for standby mode induction cooker A, the impedance equivalent parameter can be defined. The final impedance equivalent circuit parameter for operation mode of induction cooker A and the impedance curve comparison between measurement and simulation can be seen in Figure 4.8.



(a) (b)

Figure 4.8 The impedance of operation mode of induction cooker A
(a) equivalent circuit, (b) Impedance properties

The comparison of internal impedance between standby and operation mode obtained from measurement and simulation is shown in Figure 4.9. The figure shows the internal impedance difference between standby and operation mode especially in the frequency range within 20-25 kHz. The impedance is almost similar for frequency above 30 kHz up to 90 kHz.



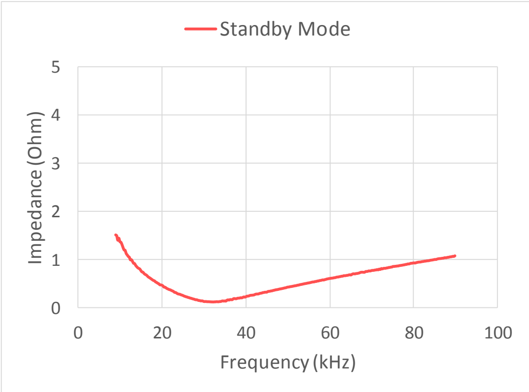
(a) (b)

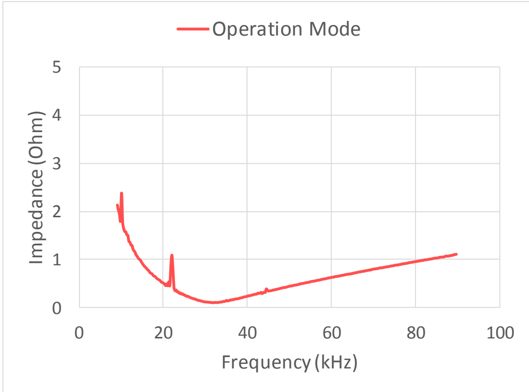
Figure 4.9 The comparison of impedance between standby and operation mode of induction cooker A
(a) Measurement, (b) Simulation

B. Induction Cooker B

The induction cooker B has also two mode options, standby and operation modes. For operation mode, there are 8 power level options of operation. For this study, the internal impedance measurement are only performed for standby mode and operation mode at the 7th power level of induction cooker B which is producing the highest disturbance level.

The impedance properties of standby mode operation of induction cooker B for frequency range within 9-90 kHz can be seen in Figure 4.10(a). Referring to the impedance curve, it can be noticed that there is one series resonance occurred at frequency of 32 kHz. At this series resonance frequency, the induction cooker A has very low impedance with impedance value of 0.13 Ohm.





(a) (b)

Figure 4.10 The impedance curve of induction cooker B
(a) standby mode (b) operation mode

The impedance properties of operation mode induction cooker B can be seen in Figure 4.10(b). The impedance contains one series resonance occurred at frequency 32 kHz with the impedance value of 0.11 Ohm. Figure 4.10 also shows a spike impedance at frequency in between 21-23 kHz due to the disturbance produced by the induction cooker B. Figure 4.11 indicates little impedance differences between standby and operational modes especially in the frequency range 20-25 kHz.

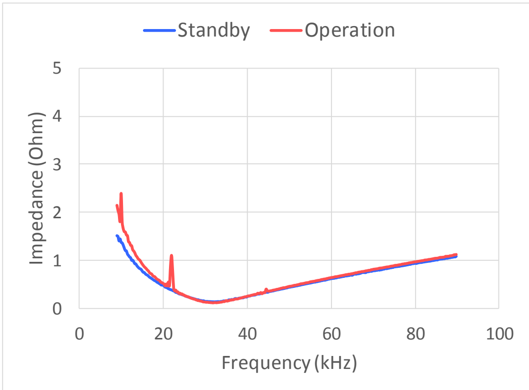
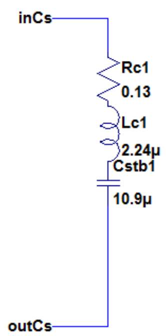
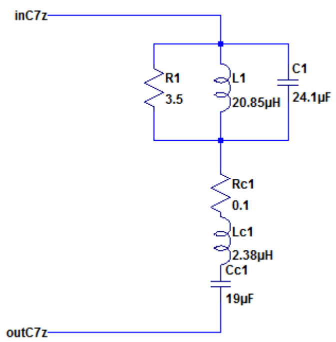


Figure 4.11 The comparison between standby and operation mode impedance of induction cooker B

Using similar calculation method in the section 2.3.2.A, the internal impedance equivalent circuit parameter can be defined. The final impedance equivalent circuit parameter for both standby and operation modes of induction cooker B can be seen in Figure 4.12.

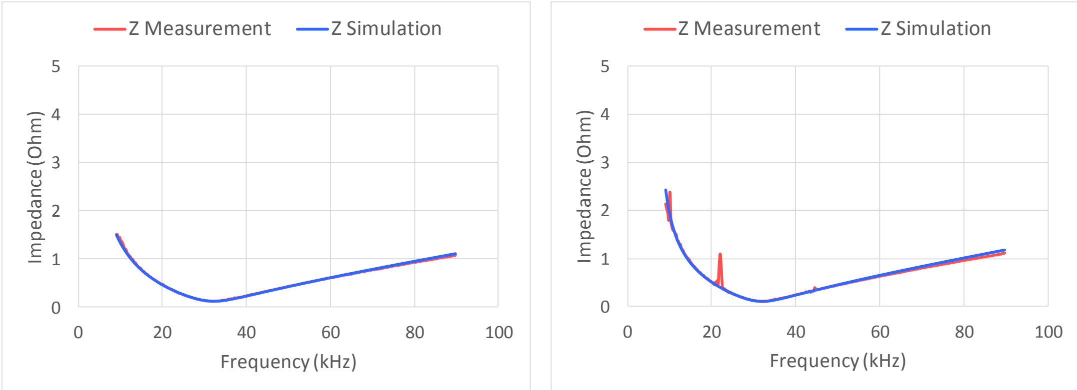




(a) (b)

Figure 4.12. The impedance equivalent circuit of induction cooker B
(a) Standby mode (b) Operation mode

The comparison of internal impedance between measurement and simulation for standby and operation mode of induction cooker B can be seen in Figure 4.13. The impedance curve from the simulation is relatively close with the impedance from measurement especially in frequency range of 20-25 kHz. This equivalent circuit then will be used later in the simulation section.

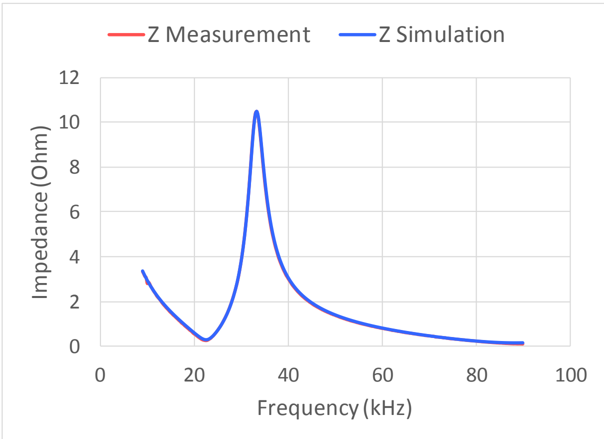
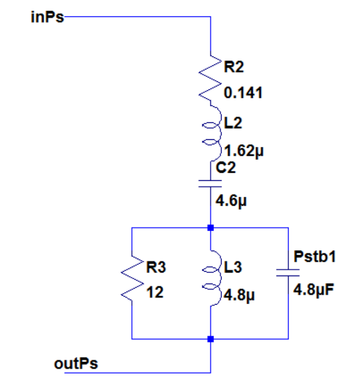


(a) (b)

Figure 4.13 The comparison between measurement and simulation impedance of induction cooker B (a) Standby mode impedance, (b) Operation mode impedance

The internal impedance and equivalent circuit parameter for the rest appliances can be seen in Table 4.1.

Table 4.1 The internal impedance and equivalent circuit of secondary appliances

<table>
<tr><th>Appliance</th><th>Internal Impedance Curve</th><th>Equivalent Circuit</th></tr>
<tr><td>Standby Mode
Inverter Microwave</td><td>
</td><td>
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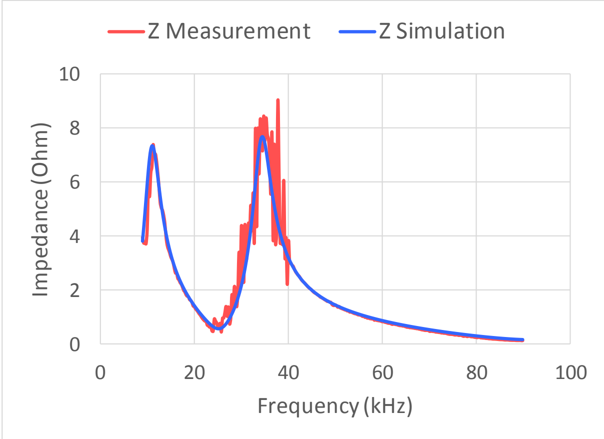
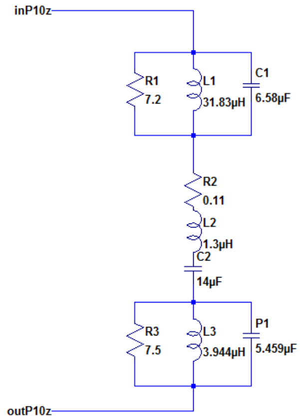
Inverter Microwave</td><td>
</td><td>
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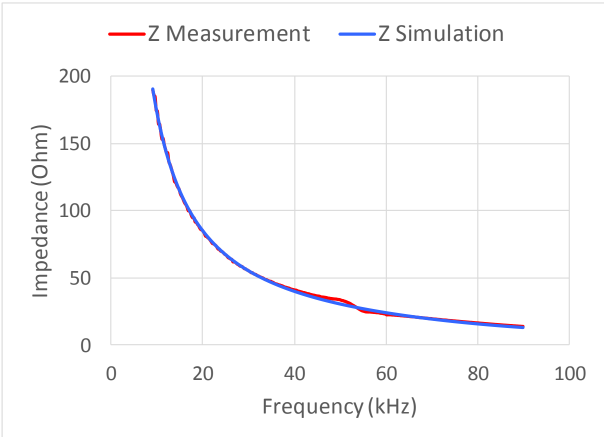
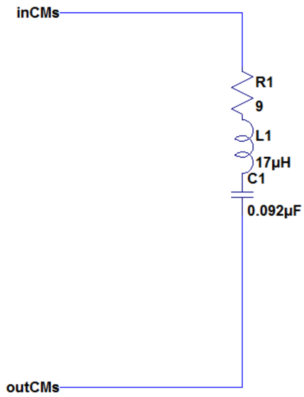
Conventional Microwave</td><td>
</td><td>
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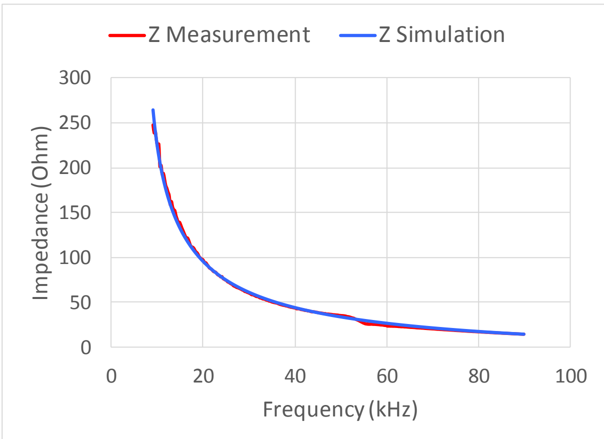
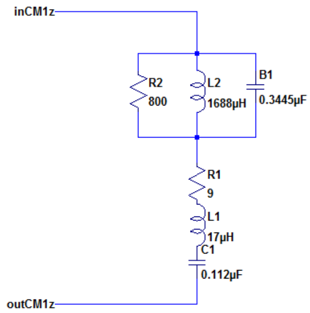
Conventional Microwave</td><td>
</td><td>
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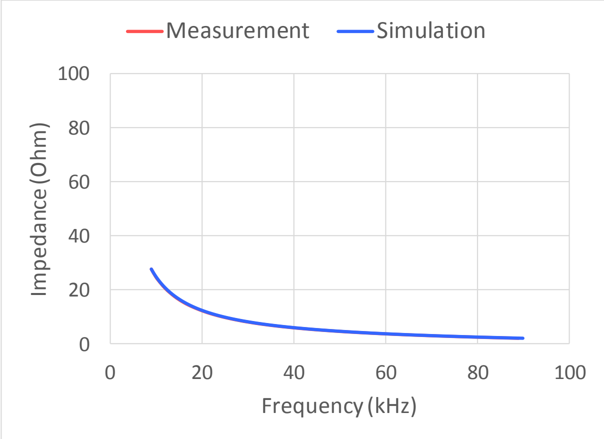
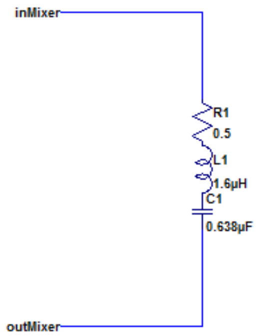
<tr><td>Operation Mode Mixer</td><td>
</td><td>
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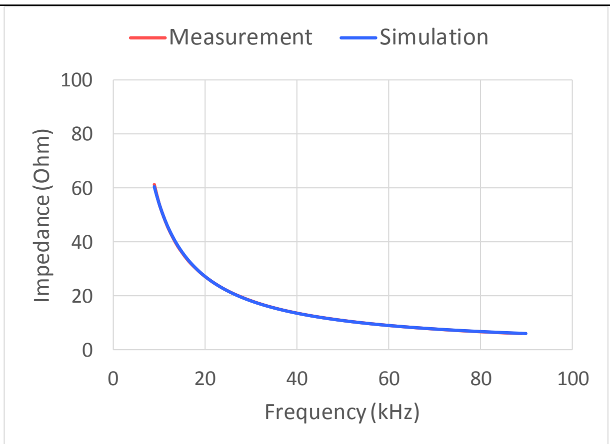
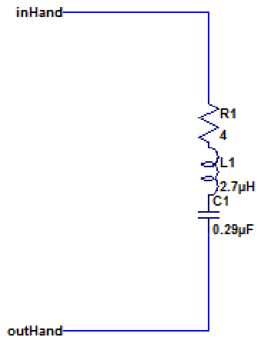
<tr><td>Operation Mode Hand Blender</td><td>
</td><td>
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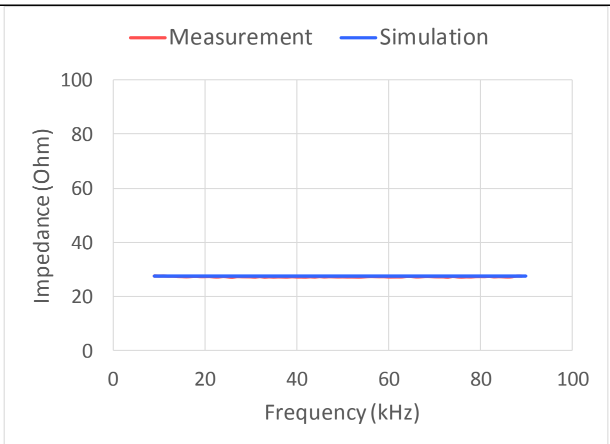
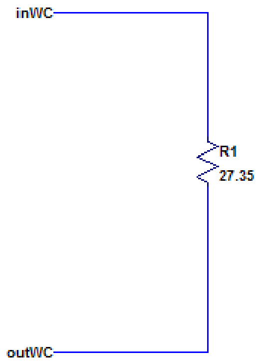
<tr><td>Operation Mode Water Cooker</td><td>
</td><td>
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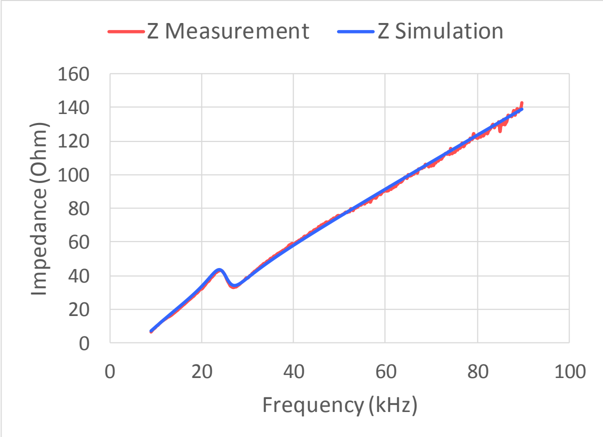
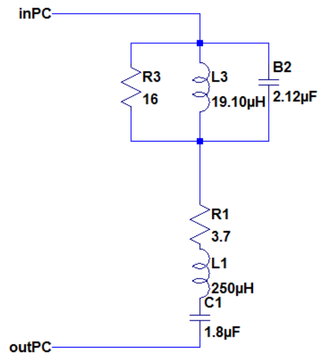
<tr><td>Operation Mode Personal Computer</td><td>
</td><td>
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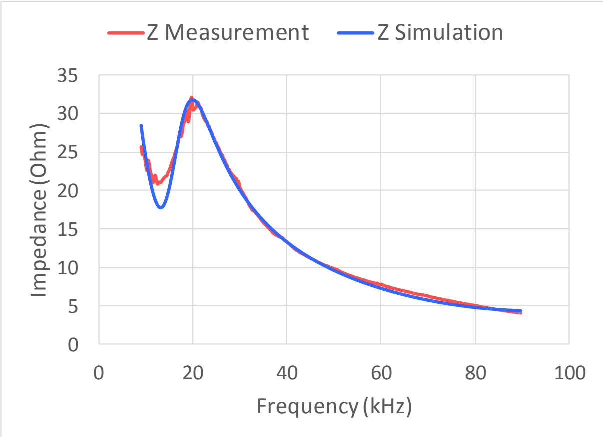
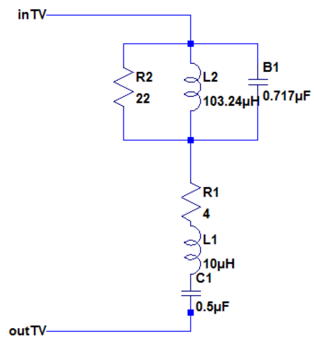
<tr><td>Operation Mode Television (TV)</td><td>
</td><td>
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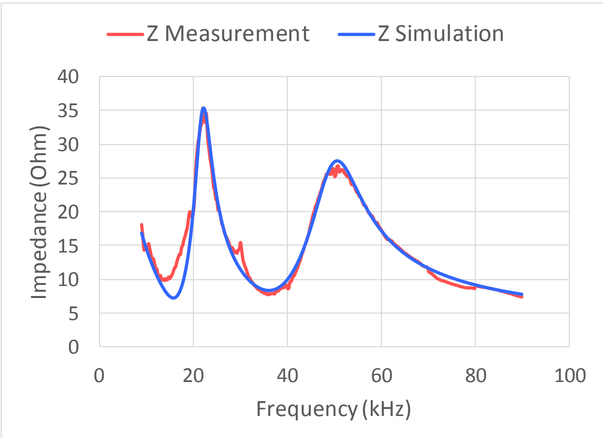
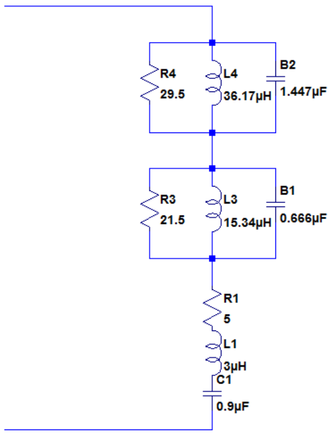
<tr><td>Operation Mode Notebook</td><td>
</td><td>
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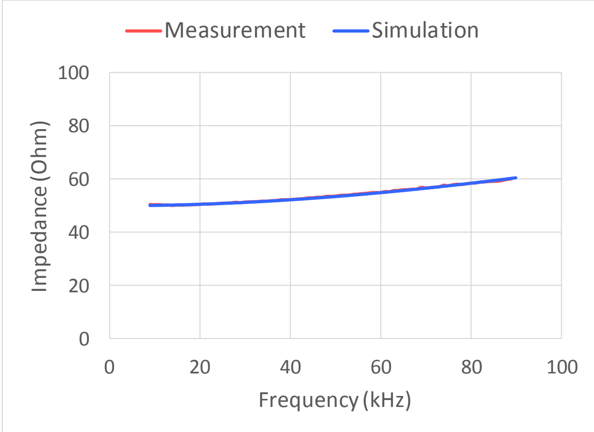
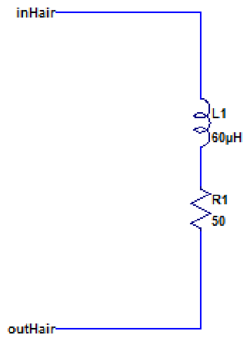
<tr><th>Appliance</th><th>Internal Impedance Curve</th><th>Equivalent Circuit</th></tr>
<tr><td>Operation Mode Personal Hair Dryer</td><td>
</td><td>
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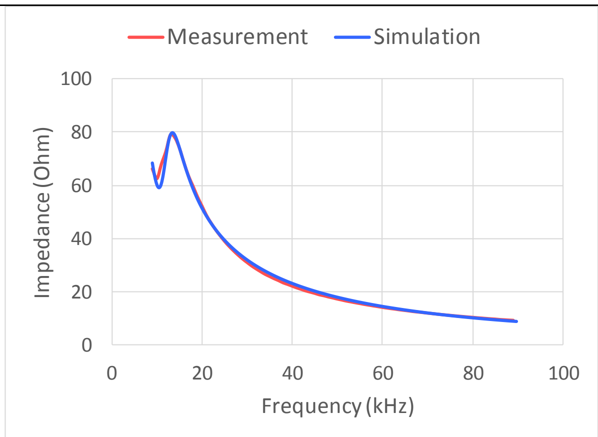
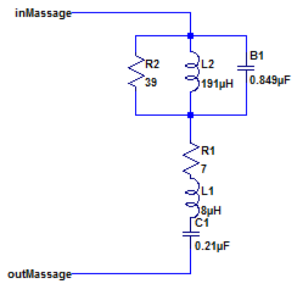
<tr><td>Operation Mode Electric Massage</td><td>
</td><td>
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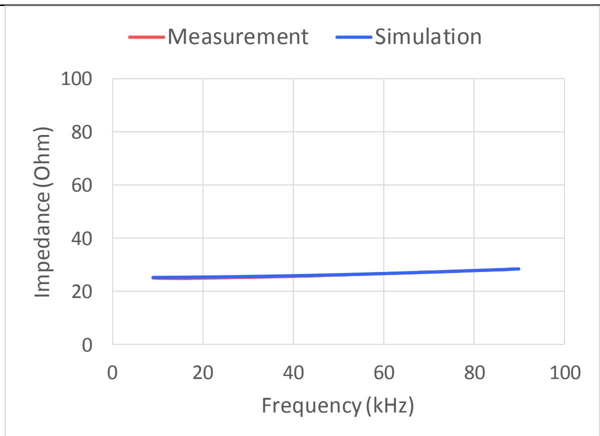
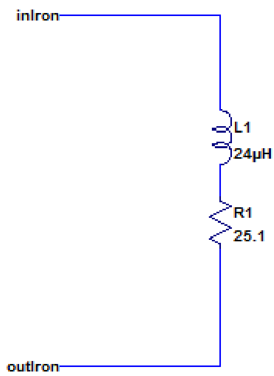
<tr><td>Operation Mode Iron</td><td>
</td><td>
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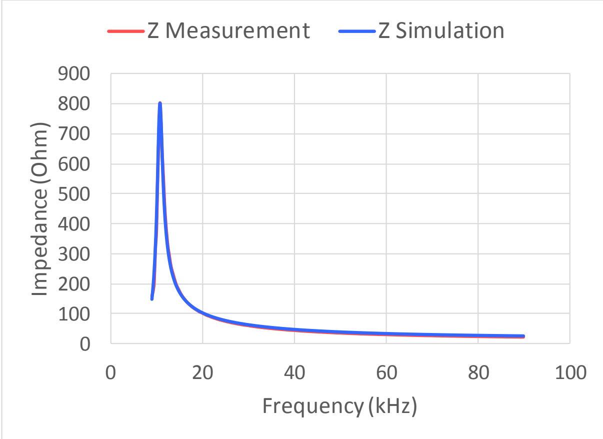
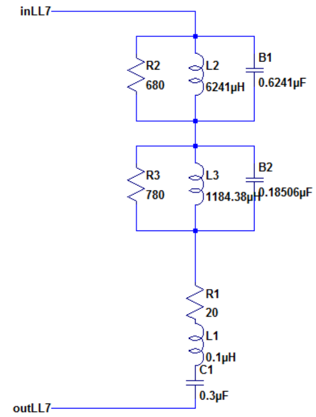
<tr><th>Appliance</th><th>Internal Impedance Curve</th><th>Equivalent Circuit</th></tr>
<tr><td>LED Lamp</td><td>
</td><td>
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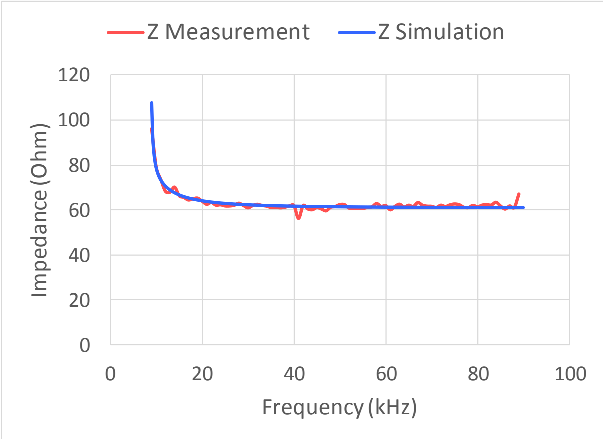
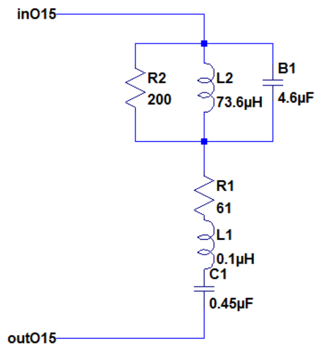
<tr><td>Compact Fluorescent Lamp</td><td>
</td><td>
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</table>

The measurement results give several characteristics related to the internal impedance properties of appliances in the frequency range 9 kHz to 90 kHz. Each appliance has specific impedance values that vary over frequency. For appliances equipped with EMC Filter, the impedance may contain series resonance that has very low impedances in the specific range of frequency. For appliances with two state modes, the internal impedance in standby mode is different from that in operation mode. The appliances depending on their internal impedance properties can act as filter or amplifier to the disturbance signal in the low voltage network. When the impedance is low in specific frequency range, the appliance can act as a filter for both intentional and unintentional signal.

4.3 Equivalent Circuit of Appliances

The equivalent circuit of appliance contains two main parameters, the disturbance properties and the internal impedance of appliance as can be seen in Fig 4.14. By referring the disturbance properties of individual appliance obtained in Chapter 3 and the internal impedance characteristics of each appliance obtained in subsection 4.2, the equivalent circuit parameter of appliances can be determined and constructed.

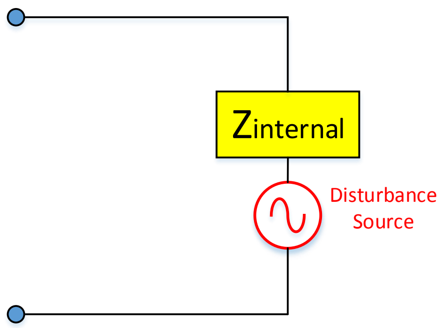


Figure 4.14. The model of equivalent circuit of appliance

Generally, the internal impedance of appliance is almost constant for different supply voltage levels, while the disturbance produced by some appliances is affected by the variation of supply voltage level. Hence, the equivalent circuit of appliance may differ for different supply voltage levels. The equivalent circuits of induction cooker A and B for different supply voltage levels of 224 V, 221 V and 218 V are explained below as an example.

For induction cooker A, the internal impedance of operation mode is shown in Figure 4.6(a) while the disturbance levels and frequency properties produced by induction cooker A at supply voltage levels of 224 V, 221 V and 218 V are shown in Table 4.2.

Table 4.2 The disturbance properties produced by induction cooker A

V mains	Disturbance Frequency	Disturbance Level
(Volt)	(Hz)	(Volt)
224	22600	3.701
221	22400	4.035
218	22300	4.151

The equivalent circuit of induction cooker A for mains voltage levels 224 V, 221 V and 218 V can be seen in Figure 4.15.

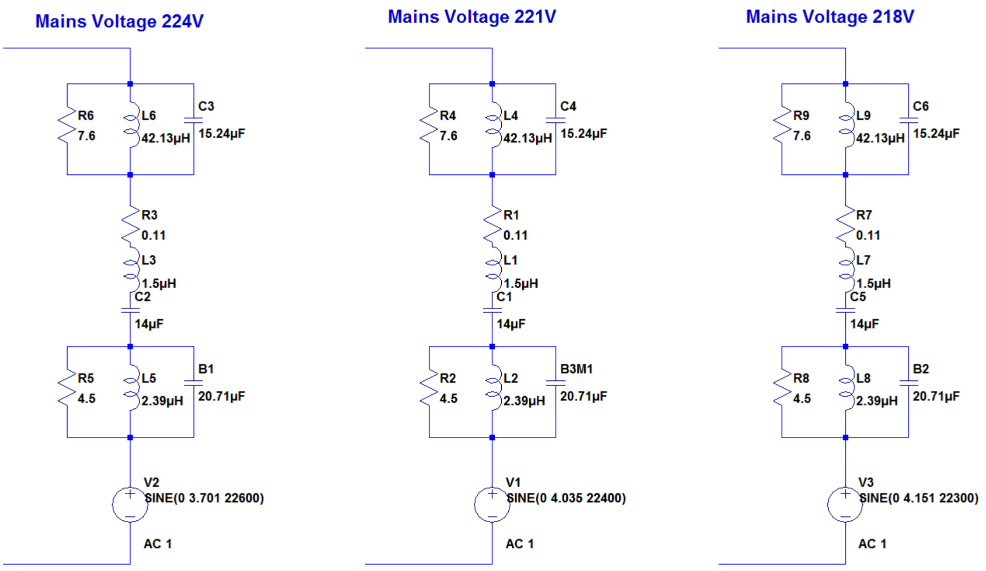


Figure 4.15 The equivalent circuit of induction cooker A for 3 supply voltage levels

The same method is also applied for induction cooker B. The internal impedance of operation mode is shown in Figure 4.12(b) while the disturbance levels and frequency properties produced by induction cooker B at supply voltage levels of 224 V, 221 V and 218 V are shown in Table 4.3.

Table 4.3. The disturbance properties produced by induction cooker B

V mains	Disturbance Frequency	Disturbance Level
(Volt)	(Hz)	(Volt)
224	22300	0.207
221	22200	0.219
218	21900	0.234

The equivalent circuit of induction cooker B for mains voltage levels 224 V, 221 V and 218 V can be seen in Figure 4.16.

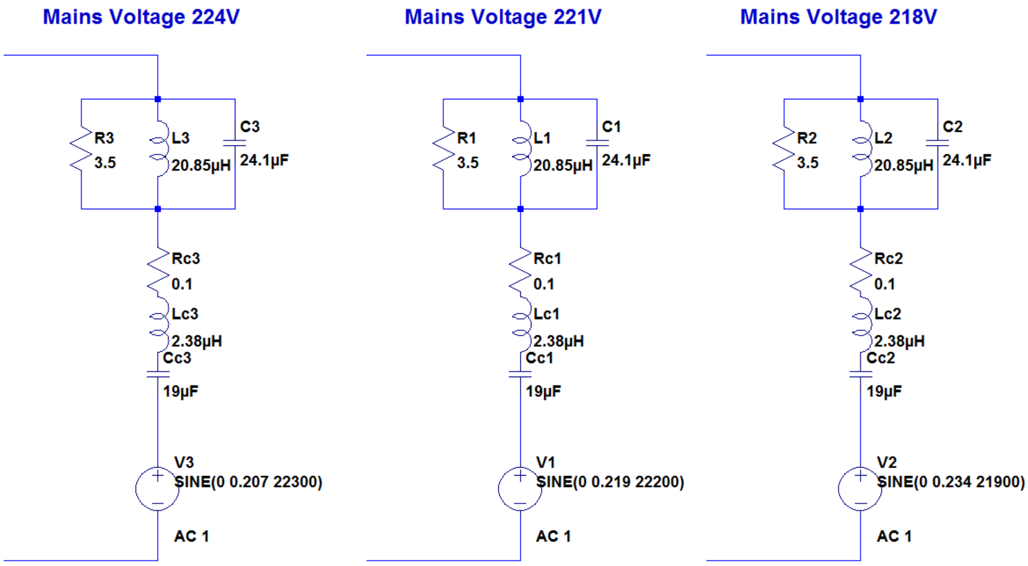


Figure 4.16 The equivalent circuit of induction cooker B for 3 supply voltage levels

The equivalent circuit of appliances will be used in the calculation to analyze and validate the disturbance occurred in the network for simultaneous operation of appliances (Chapter 5). Moreover, the equivalent circuits will also be used in the simulation of disturbance in residential network environment (Chapter 6).

CHAPTER 5
BEHAVIOR OF DISTURBANCE FOR SIMULTANEOUS OPERATION OF APPLIANCES

This section is focused on observing the behavior of disturbance when two appliances are connected simultaneously to the network. The aim is to define the effect of neighbor appliance to the disturbance produced by another appliance. The first appliance is operated as the disturbance source while the second appliance is operated as the neighbor appliance. The appliances chosen as the disturbance source are induction cooker A and induction cooker B while the appliances chosen as the neighbor appliances are inverter based microwave, conventional microwave, mixer, hand blender, water cooker, personal computer, notebook, TV led, hairdryer, electric massage, iron, compact fluorescent lamp and led lamp.

There are 2 testing schemes which will be performed as can be seen in Figure 5.1. The first scheme is the interaction between appliances at adjusted mains voltage and the second scheme is the interaction between appliances at natural mains voltage. The mains network impedance is set constant viewed from the EUT side by inserting a decoupling network circuit which has constant high impedance to omit the variation of real mains network impedance. The decoupling network circuit is also used to block the disturbance originating from mains network entering the EUT side and vice versa. The disturbance result then will be analyzed and validated by referring the properties of the disturbance and the internal impedance of disturbance source appliance, the internal impedance of neighbor appliance, and the impedance of controlled mains network.

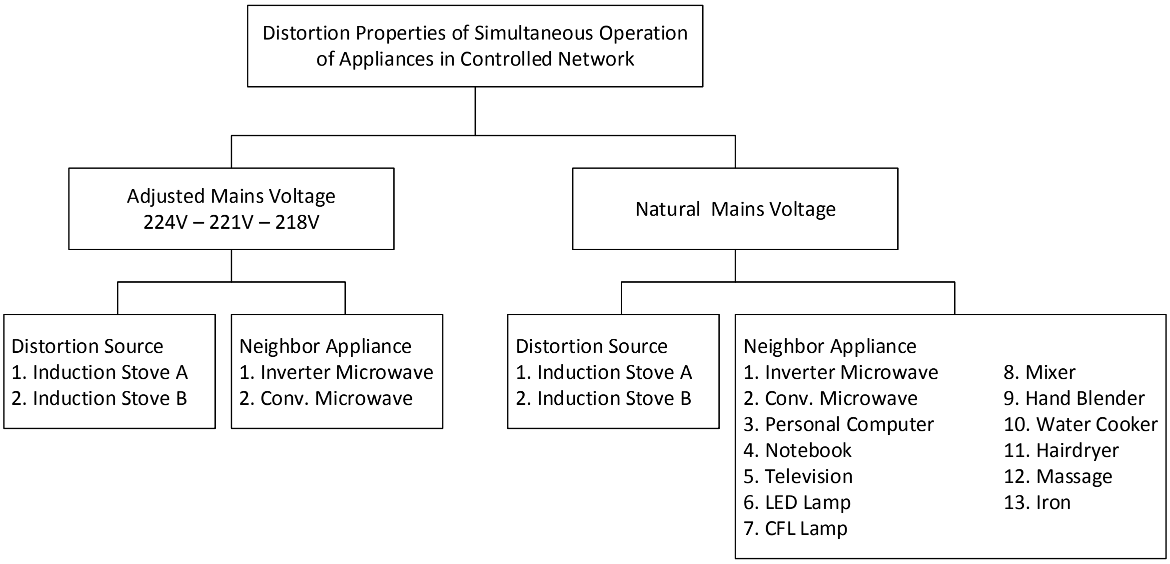


Figure 5.1 Testing schemes of disturbance properties for simultaneous operation of appliances

5.1 Interaction Between Appliances at Adjusted Mains Voltage

The testing at adjusted mains voltage aims to define the disturbance interaction behavior when the appliances are operated simultaneously at certain mains voltage level. The mains voltage level is set and kept constant during the test at three levels of 224 V, 221 V, and 218 V. Since two network properties variables are kept constant (mains voltage level and mains network impedance), the observation of the disturbance behavior for simultaneous operation of appliances could be done by only counting the internal impedance of participating appliances. The scheme for this testing can be seen in Figure 5.2. The decoupling network circuit consists of 1 mH + 10 uF + 1 mH. The variation of supply voltage level is obtained by adjusting the autotransformer.

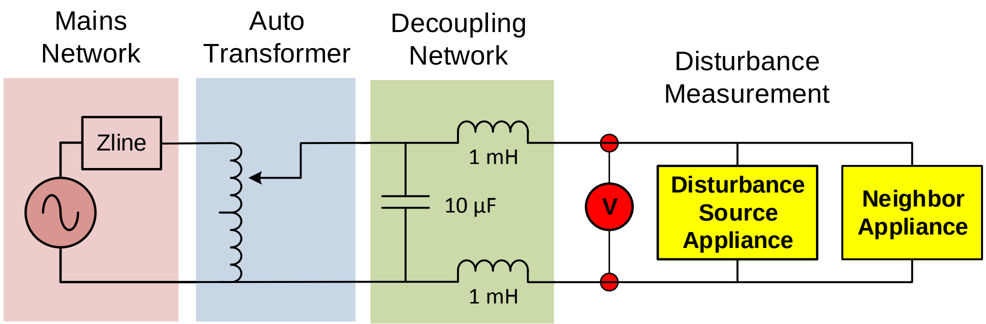


Figure 5.2 The testing scheme of simultaneous operation of appliance at adjusted voltage level

The induction cooker A and induction cooker B are used as disturbance sources due to their high disturbance level and internal impedance difference. The inverter microwave and conventional microwave are chosen as the neighbor appliances since they have low and high impedance values at the frequency of disturbance (21-24 kHz). The inverter microwave and conventional microwave will be operated in standby mode operation. The impedance properties of induction cooker A, induction cooker B, inverter microwave and conventional microwave in the frequency range within 15-40 kHz can be seen in Figure 5.3.

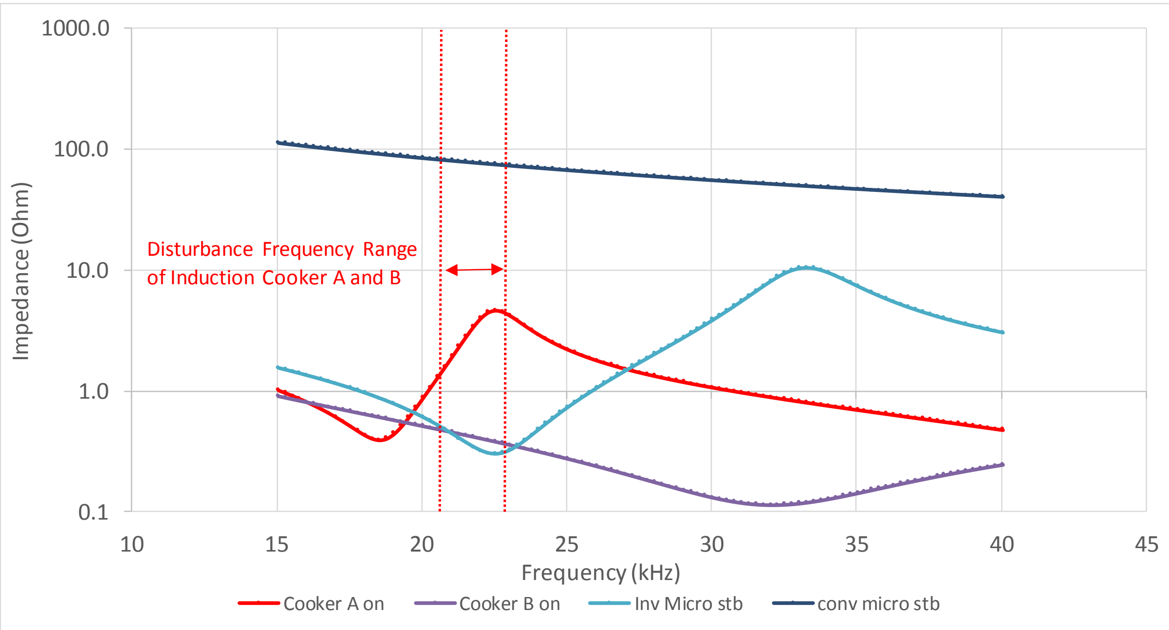


Figure 5.3 The internal impedance of appliances in the frequency range within 15-40 kHz

The discussion of this testing will be divided into two subsections. The first section observes the disturbance characteristics when the low impedance appliance (inverter microwave) is operated as the neighbor appliance while the second section observes the disturbance when the high impedance appliance (conventional microwave) is operated as the neighbor appliance.

5.1.1 Effect of Low Internal Impedance of Neighbor Appliance

The first testing is performed by operating the induction cooker A and B as the disturbance source appliance while the inverter microwave (low internal impedance appliance) is operated as the neighbor appliance. There are 2 testing schemes conducted for this section as can be seen in Table 5.1.

Table 5.1 Testing scheme for observing the effect of low internal impedance neighbor appliance

Scheme	Distortion Source		Neighbor Appliance	
	Appliance	Mode	Appliance	Mode
A	Ind. Cooker A	Operation	Inv. Microwave	Standby
B	Ind. Cooker B	Operation	Inv. Microwave	Standby

A. Induction cooker A as the disturbance source appliance

To observe the effect of low internal impedance neighbor appliances to the disturbance produced by induction cooker A, the disturbance produced by induction cooker A when operated individually should be defined first. The disturbance level and frequency produced by induction cooker A when operated individually can be seen in Table. 4.2. The measurement result of disturbance appeared in the network for this testing scheme is shown in Table 5.2.

Table 5.2 The disturbances appeared in the network when standby mode inverter microwave is operated as neighbor appliance

V mains	Individual	Simultaneous Operation	
	Ind. Cooker A	Ind Cooker A + Inv. Microwave	
	Disturbance	Disturbance	Reduction
(Volt)	(Volt)	(Volt)	%
224	3.701	0.238	93.6
221	4.035	0.264	93.5
218	4.151	0.272	93.4

Initially, the induction cooker A is operated and connected to the controlled network at mains voltage level 224 V. The disturbance occurred in network when the induction cooker A is operated individually is 3.701 V. The standby mode inverter microwave is then connected to the network while the mains voltage is maintained to 224 V. The disturbance occurred in the network decreases from 3.701 V to 0.238 V, so that there is a disturbance reduction of 93.6 %. Referring to the internal impedance property of standby mode inverter microwave as shown in Figure 5.3, the impedance of inverter microwave at frequency 22600 Hz is 0.28 Ohm (see Appendix A). This low internal impedance of inverter microwave filters the disturbance produced by induction cooker A and consequently decreases the disturbance appeared in network. For the mains voltage 221 V, the disturbance occurred in the network is 4.035 V when the induction cooker A is operated individually. The disturbance then decreases to 0.264 V when the standby inverter microwave is connected to the network, so that there is a disturbance reduction of 93%. The similar condition is also happened for mains voltage level of 218 V as can be seen in Table 5.2. When the standby mode inverter microwave is connected, the disturbance decreases from 4.151 V to 0.272 V. It can be noticed that the low internal impedance neighbor appliance (standby mode inverter microwave) reduces significantly the disturbance occurred in the network. The reduction level is influenced by the internal impedance properties of appliances (disturbance source and neighbor appliance) at the disturbance frequency.

Since the internal impedance and the disturbance characteristics of EUTs have been defined in Chapter 3 and 4, the disturbance occurred in the network can be calculated. Three properties needed for this disturbance calculation are the equivalent circuit of induction cooker A as the disturbance source, the inverter microwave as the neighbor appliance, and the controlled mains network. The equivalent circuit of induction cooker A for mains voltage levels 224 V, 221 V and 218 V can be seen in Figure 4.12, while the equivalent circuit of standby mode inverter microwave and controlled mains network can be seen in Figure 5.4.

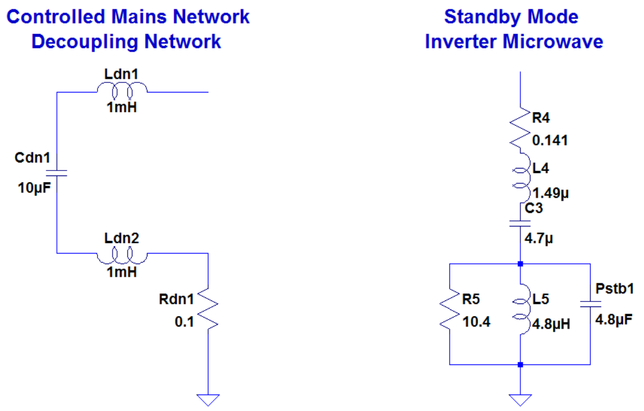


Figure 5.4 The equivalent circuit of controlled mains network and standby mode inverter microwave

By referring the equivalent circuit of appliances and mains network, the circuit for the test of interaction between operation mode induction cooker A and standby mode inverter microwave in controlled mains network at mains voltage level of 224 V can be seen in Figure 5.5 below.

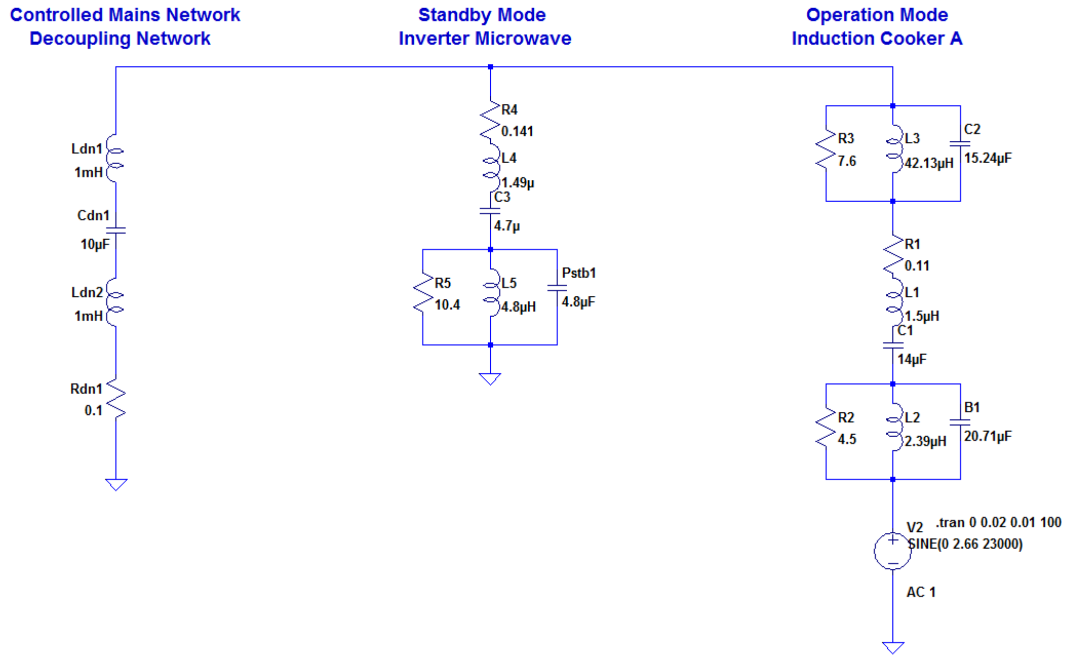


Figure 5.5 The equivalent circuit of interaction between induction cooker A and standby mode inverter microwave in controlled mains network for mains voltage level 224 V

The frequency of disturbance generated by induction cooker A at mains voltage level of 224 V is 22600 Hz as can be seen in the equivalent circuit. The impedance of each section (induction cooker A, inverter microwave and mains network) for frequency 22600 Hz can be calculated as follows.

The impedance of controlled mains network:

$Z_{\text{mains}} = (0.1 + j284 - j0.704)\ \Omega$

$Z_{\text{mains}} = (0.1 + j283.3)\ \Omega$

The internal impedance of standby mode inverter microwave:

$Z_{\text{invmicro}} = \left((0.141 + j0.212 - j1.498)\ + (10.4//j0.682//{-j}1.467)\right)\ \Omega$

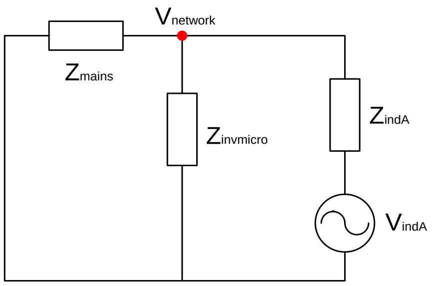
$Z_{\text{invmicro}} = (0.299\ + j\ 0.033)\ \Omega$

The internal impedance of operation mode induction cooker A:

$Z_{\text{indA}} = ((7.6//j5.982//{-j}0.462)\ + (0.11 + j0.213 - j0.503)\ + (4.5//j0.339//{-j}0.340))\ \Omega$

$Z_{\text{indA}} = (4.472 - j\ 0.682)\ \Omega$

The voltage occurred in the network (common point) can be obtained using voltage divider equation.



$$V_{\text{network}} = \frac{Z_{\text{mains}}//Z_{\text{invmicro}}}{Z_{\text{indA}} + (Z_{\text{mains}}//Z_{\text{invmicro}})} * V_{\text{indA}}$$

Since the disturbance voltage produced by induction cooker A for mains voltage level 224 V is 3.701 V, the disturbance voltage occurred in the network is

$V_{\text{network}} = \frac{0.299 + \ j\ 0.033}{4.771 - j\ 0.649} * 3.701\angle 0°$ Volt

$V_{\text{network}} = (0.0606 + j\ 0.0152) * 3.701\angle 0°$ Volt

$V_{\text{network}} = \ 0.224 + j\ 0.056 = 0.232\angle 14°$ Volt

The value of disturbance voltage appeared in the network gathered from the calculation is close to the value of disturbance obtained from the measurement. The difference between measurement and calculation is

$$V_{\%\text{error}} = \frac{|V_{\text{measurement}} - V_{\text{calculation}}|}{V_{\text{measurement}}} * 100\%$$

$$V_{\%\text{error}} = \frac{|0.238 - 0.232|}{0.238} * 100\% = 2.4\%$$

Using similar method, the difference of voltage disturbance obtained from measurement and calculation for the mains voltage levels 221 V and 218 V can be obtained. The calculation results of the disturbance appeared in the network and the percent disturbance difference between measurement and calculation for all mains voltage levels are shown in Table 5.3.

Table 5.3 The comparison of disturbance obtained from measurement and calculation

V mains	Disturbance Frequency	Disturbance		Error
		Measurement	Simulation	
(Volt)	(Hz)	(Volt)	(Volt)	%
224	22600	0.238	0.232	2.4
221	22400	0.264	0.258	2.3
218	22300	0.272	0.274	0.7

B. Induction cooker B as the disturbance source appliance

The testing scheme is performed by connecting the induction cooker B as the disturbance source appliance and the standby mode inverter microwave as the neighbor appliance to the controlled mains network. The mains voltage levels are set to 224 V, 221 V and 218 V. The disturbance level and frequency produced by induction cooker B when operated individually can be seen in Table 4.3. The disturbance level and frequency produced by induction cooker B for three mains voltages are summarized in Table 5.4.

Table 5.4 shows the measurement results of disturbances appeared in the network for all mains voltage levels. It can be noticed that when the inverter microwave is operated as the neighbor appliance, the disturbance appeared in the network is decreased significantly. At the mains voltage level of 224 V, the disturbance appeared in the network changes from 0.207 V when induction cooker A operated individually to 0.109 V when standby mode inverter microwave is connected as neighbor appliance. The disturbance reduction for this testing is 49,5 %. Table 5.4 also shows that the disturbance reduction is higher for lower main voltage levels due to the differences of internal impedance of appliances at different disturbance frequency. The internal impedance characteristics can be seen in Figure 5.3.

Table 5.4 The measurement results of disturbances appeared in the network when low internal impedance neighbor appliance is connected

V mains	Individual	Simultaneous Operation	
	Ind. Cooker B	Ind Cooker B + Inv. Microwave	
	Disturbance	Disturbance	Reduction
(Volt)	(Volt)	(Volt)	%
224	0.207	0.109	47.4
221	0.219	0.112	48.9
218	0.234	0.116	50.6

The disturbance occurred in the network for this scheme can also be calculated using similar method as described in section 5.1.1.A. The calculation of disturbance appeared in the network and the percent disturbance difference between measurement and calculation for all mains voltage level is shown in Table 5.5.

Table 5.5 The comparison of disturbance obtained from measurement and calculation

V mains	Disturbance Frequency	Disturbance		Error
		Measurement	Simulation	
(Volt)	(Hz)	(Volt)	(Volt)	%
224	22500	0.109	0.107	1.6
221	22300	0.112	0.108	3.6
218	22100	0.116	0.112	3.1

Referring to the measurement and calculation results when low internal impedance neighbor appliance (standby mode inverter microwave) is operated simultaneously with disturbance source appliance (induction cooker A and B), several points can be summarized as follows:

- The low internal impedance neighbor appliance (standby mode inverter microwave) reduces the disturbance appeared in the network significantly.
- Comparing the reduction of disturbance produced by induction cooker A and B when low impedance neighbor appliance (standby mode inverter microwave) is connected simultaneously to the network, it can be noticed that low impedance neighbor appliance gives different effect to the disturbance. The disturbance reduction of induction cooker A is higher (93.6 %, 93.5 % and 93.4 %) than it is for induction cooker B (47.4 %, 48.9 % and 50.6 %). This result shows that the internal impedance of disturbance source appliance (induction cooker A and B) influences the effect given by the neighbor appliance to the disturbance appeared in the network.
- The calculation of disturbance using the equivalent circuit data gives a close value with the disturbance gathered from the measurement. The maximum disturbance difference in this testing scheme is 3.6 %. Since the disturbance difference between measurement and calculation is relatively small, the equivalent circuit of appliance can be used for simulation purposes.

5.1.2 The Effect of High Impedance Neighbor Appliance

The second testing is performed by operating the induction cooker A and B as the disturbance source appliance while the standby mode conventional microwave (high internal impedance appliance) is operated as neighbor appliance. There are 2 testing schemes conducted for this section as can be seen in Table 5.6.

Table 5.6 The testing scheme for observing the effect of high internal impedance neighbor appliance

Scheme	Distortion Source		Neighbor Appliance	
	Appliance	Mode	Appliance	Mode
A	Ind. Cooker A	Operation	Conv. Microwave	Standby
B	Ind. Cooker B	Operation	Conv. Microwave	Standby

A. Induction Cooker A as The Disturbance Source Appliance

The testing scheme is performed by connecting the induction cooker A as the disturbance source appliance and the standby mode conventional microwave as neighbor appliance to the mains network. The mains voltage levels are set constant to 224 V, 221 V and 218 V. Table 5.7 shows the measurement result of disturbance appeared in the network for all mains voltage levels.

According to the table 5.7, when the conventional microwave is operated as neighbor appliance, the disturbance appeared in the network does not change significantly. For example, when the mains voltage level is 224 V, the disturbance appeared in the network only changes from 3.701 V when induction cooker A operated individually to 3.616 V when standby mode conventional microwave is connected as neighbor appliance. The disturbance reduction for this testing is only 2.3 % and getting higher for a lower main voltage level due to the difference of internal impedance of appliances on difference disturbance frequency. Since the internal impedance of conventional microwave is relatively high compared to the internal impedance of induction cooker A as the disturbance source, there is no significant effect given by conventional microwave to the disturbance appeared in the network.

Table 5.7 Measurement results of disturbances appearing in the network when the conventional microwave is operated as neighbor appliance in standby and operation modes

V mains	Individual	Simultaneous Operation	
	Ind. Cooker A	Ind Cooker A + Conv. Microwave	
	Disturbance	Disturbance	Reduction
(Volt)	(Volt)	(Volt)	%
224	3.701	3.616	2.3
221	4.035	3.940	2.3
218	4.151	4.130	0.5

The disturbance occurred in the network for this scheme can also be calculated using similar method as described in the previous section. The calculation of voltage disturbance occurred in the network and the percent disturbance difference between measurement and calculation for all mains voltage levels is shown in table 5.8.

Table 5.8 Comparison of disturbance obtained from measurement and calculation

V mains	Disturbance Frequency	Disturbance		Error
		Measurement	Simulation	
(Volt)	(Hz)	(Volt)	(Volt)	%
224	22700	3.616	3.684	1.9
221	22500	3.940	4.002	1.6
218	22400	4.130	4.109	0.5

B. Induction Cooker B as The Disturbance Source Appliance

The testing scheme is performed by connecting the induction cooker B as the disturbance source appliance and the conventional microwave as neighbor appliance to the mains network. The inverter microwave operated in both standby and operation modes. Table 5.9 shows the measurement results of disturbances appeared in the network for all mains voltage levels. When the conventional microwave is operated as neighbor appliance, the disturbance appeared in the network is changed very little or even remaining constant.

Table 5.9 Measurement result of disturbance appearing in the network when the conventional microwave is operated as neighbor appliance in standby and operation modes

V mains	Individual	Simultaneous Operation	
	Ind. Cooker B	Ind Cooker B + Conv. Microwave	
	Disturbance	Disturbance	Reduction
(Volt)	(Volt)	(Volt)	%
224	0.207	0.202	2.1
221	0.219	0.216	1.5
218	0.234	0.225	3.8

The disturbance occurred in the network for this scheme can also be calculated using similar method as described in section 5.2.1.A. The calculation of voltage disturbance appeared in the network and the percent voltage difference between measurement and calculation for all mains voltage levels is shown in Table 5.10.

Table 5.10 Comparison of disturbance obtained from measurement and calculation

V mains	Disturbance Frequency	Disturbance		Error
		Measurement	Simulation	
(Volt)	(Hz)	(Volt)	(Volt)	%
224	22500	0.202	0.207	2.3
221	22200	0.216	0.219	1.4
218	22100	0.225	0.233	3.6

Referring to the measurement and calculation/simulation when high internal impedance neighbor appliance (standby mode conventional microwave) is operated simultaneously with disturbance source appliance (induction cooker A and B), several points can be summarized as follows:

- The high internal impedance neighbor appliance (standby mode inverter microwave) does not give significant effect to the disturbance appeared in the network.
- The calculation of disturbance using the equivalent circuit data provides a close value with the disturbance gathered from the measurement. The maximum disturbance difference in this testing scheme is 3.6%. Since the disturbance difference between measurement and calculation is relatively small, the equivalent circuit of appliance can be used for simulation purposes.

5.2 Interaction Between Appliances at Natural Mains Voltage

The testing aims to determine the disturbance properties and behavior when appliances are operated simultaneously at natural mains voltage in controlled mains network. The natural mains voltage condition means that there is no adjustment to the mains voltage level during the test, so that the voltage level may decrease or increase during the test due to the variation of the EUT connected to the network. The mains network impedance is set constant viewed from the EUT side by inserting decoupling network circuit which has constant high impedance value. The scheme for this testing can be seen in Figure 5.6.

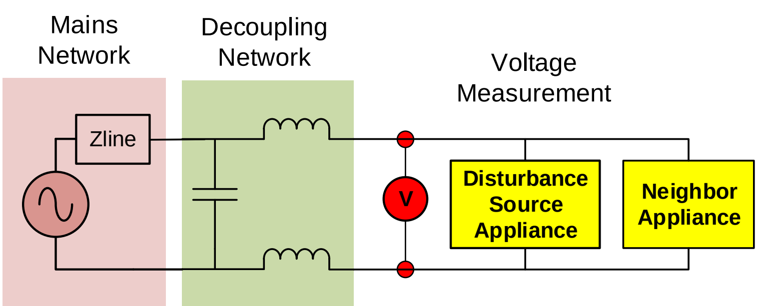


Figure 5.6 The testing scheme of simultaneous operation of appliance at adjusted voltage level

The initial mains voltage level at no load condition was in between 230 V – 231 V. The appliances chosen as the source of disturbance are induction cooker A and B while the neighbor appliances are inverter microwave, conventional microwave, mixer, hand blender, water cooker, personal computer (CPU), notebook, television LED, hair dryer, electric massage, iron, compact fluorescent lamp and LED lamp. The impedance properties of all EUT in the frequency range within 15-40 kHz can be seen in Figure 5.7.

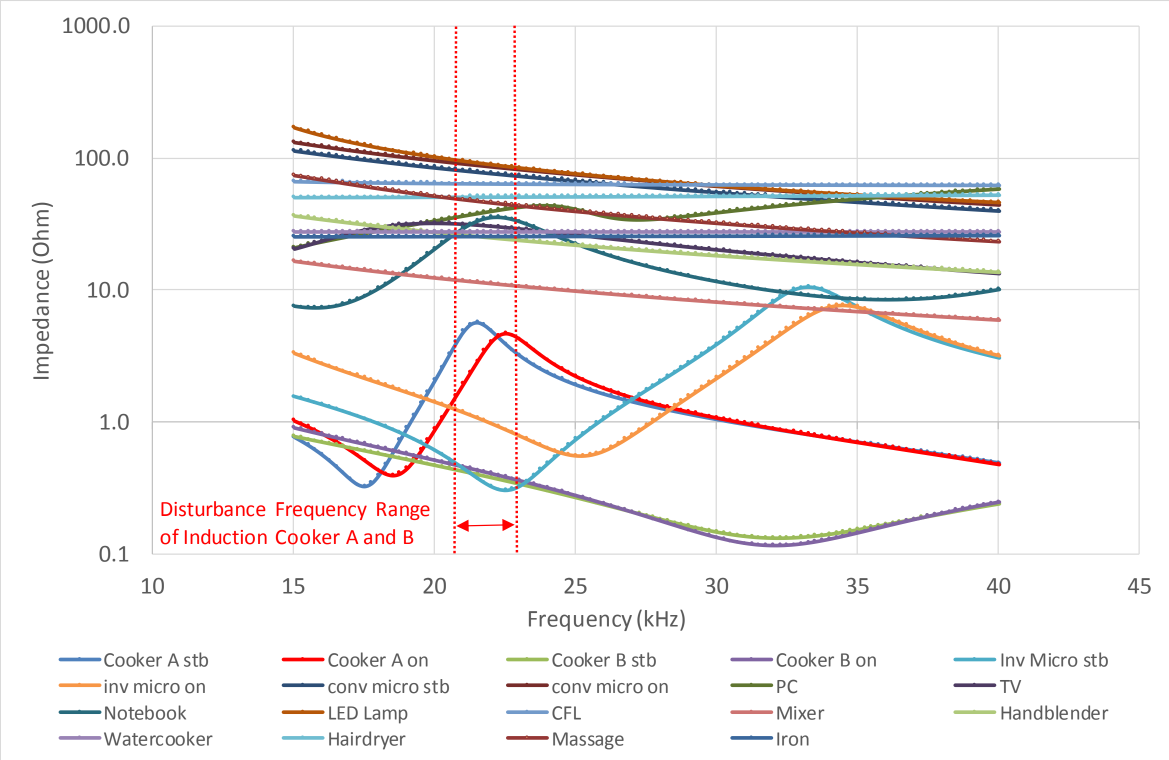


Figure 5.7 The internal impedance of all participated EUT in the frequency range within 15-40 kHz

The discussion of this testing will be divided into two subsections. The first section observes the disturbance characteristics when the induction cooker A is operated as the disturbance source appliance while the second section observes the disturbance when the induction cooker B is operated as the disturbance source appliance.

5.2.1 Induction Cooker A as Disturbance Source Appliance

The first testing is performed by operating the induction cooker A as the disturbance source appliance while other EUTs are operated as neighbor appliances. There are 16 testing steps performed for this section. The testing step and measurement result for this section can be seen in Table 5.11.

At the 1st step, the induction cooker A is operated and connected to the network individually. When the induction cooker A is connected to the mains network, the mains voltage drops from 230.5 V to 228.5 V. The disturbance level measured in the network is 2.663 V. The induction cooker A will always be connected and operated for all remaining steps of the test.

At the 2nd step, the standby mode (STB) inverter microwave was connected to the network. The mains voltage as this step is 228.5 V. There is almost no additional voltage drop due to the small current draws by standby mode inverter microwave. The disturbance measured in the mains network is 0.183 V. At this scheme, the disturbance is decreased by 93.6 % (from 2.663 V to 0.183 V).

The 3rd step is connecting the operation mode (ON) inverter microwave. The mains voltage level at this scheme drops to 225 V. The disturbance measured in the mains network is 0.565 V, meaning that the disturbance is decreased by 76.9% (from 2.663 V to 0.565 V).

Table 5.11 Measurement result when induction cooker A is used as disturbance source

Step	Disturbance Source		Neighbor		V Mains	Disturbance
	Appliance	Mode	Appliance	Mode	(Volt)	(Volt)
Step 1	Ind. Cooker A	ON	None		228.5	2.663
Step 2	Ind. Cooker A	ON	Inv. Microwave	STB	228.5	0.183
Step 3	Ind. Cooker A	ON	Inv. Microwave	ON	225.0	0.565
Step 4	Ind. Cooker A	ON	Conv. Microwave	STB	228.5	2.704
Step 5	Ind. Cooker A	ON	Conv. Microwave	ON	224.5	3.477
Step 6	Ind. Cooker A	ON	Mixer	ON	228.0	2.300
Step 7	Ind. Cooker A	ON	Hand Blender	ON	228.5	2.476
Step 8	Ind. Cooker A	ON	Water Cooker	ON	224.0	3.136
Step 9	Ind. Cooker A	ON	PC	ON	228.0	3.027
Step 10	Ind. Cooker A	ON	TV LED	ON	228	2.496
Step 11	Ind. Cooker A	ON	Notebook	ON	228.5	2.427
Step 12	Ind. Cooker A	ON	Hairdryer	ON	226.0	3.142
Step 13	Ind. Cooker A	ON	Electric Massage	ON	228.0	2.856
Step 14	Ind. Cooker A	ON	Iron	ON	224.0	3.151
Step 15	Ind. Cooker A	ON	LED Lamp	ON	228.0	2.826
Step 16	Ind. Cooker A	ON	CFL	ON	228.0	2.715

The 4th step is connecting the standby mode (STB) conventional microwave. The mains voltage at this scheme is 228.5 V. The disturbance measured in the mains network is 2.704 V. At this step, the disturbance in mains network is increased by 3.5 %.

The 5th step is connecting operation mode (ON) conventional microwave. The mains voltage level at this scheme drops to 224.5 V. There is an additional voltage drop of 4 V in mains network. The disturbance measured in the mains network is 3477 mV. The disturbance in the network is increased by 30.6 %.

The measurement result of mains voltage level and disturbance measured in the network for the 6th step up to 16th step can be seen in Table 5.12. Referring to Table 5.12, it can be noticed that each neighbor appliance gives different effect to the disturbance appeared in the network. The neighbor appliances may decrease or increase the disturbance appeared in the network.

Referring to Table 5.11, there are 2 important values obtained from the testing result. The first is the variation of mains voltage level and the second is the disturbance level occurred in the network. The mains voltage level varies from 228.5 V to 224 V during the test while the disturbance is either decreased or increased differently for each testing steps. The mains voltage level variation is caused by power consumption variation of neighbor appliances while the disturbance level is related to internal impedance of neighbor appliances and disturbance behavior of the induction cooker A. Based on the power consumption and internal impedance properties, the neighbor appliances can be classified into 4 types as can be seen in Table 5.12.

Table 5.12 Classification of neighbor appliances based on the power consumption and internal impedance properties when induction cooker A is used as disturbance source

Neighbor Type	Neighbor Appliance		Neighbor Properties	
	Appliance	Mode	Power Consumption	Internal Impedance at Disturbance Frequency
Type 1	Inverter Microwave	Standby	Low	Low
Type 2	Conv. Microwave	Standby	Low	High
	Mixer	Operation		
	Hand Blender	Operation		
	Personal Computer	Operation		
	TV LED	Operation		
	Notebook	Operation		
	Hairdryer	Operation		
	Electric Massage	Operation		
	LED Lamp	Operation		
	CFL	Operation		
Type 3	Inverter Microwave	Operation	High	Low
Type 4	Conv. Microwave	Operation	High	High
	Water Cooker			
	Iron			

Regarding to the mains voltage variation, the disturbance produced by induction cooker A is influenced by the mains voltage level as explained in the section 3.1. The measurement of disturbance level produced by induction cooker A at mains voltage 228.5 V to 223.5 V (related to the voltage variation in this testing) can be seen in Table 5.13.

Table 5.13 The disturbance produced by induction cooker A for mains voltage range 228.5 V-224 V

Vmains	Disturbance	
	Level	Frequency
(V)	(mV)	(Hz)
228.5	2663	23000
228.0	2842	23000
226.0	3284	22800
225.0	3550	22600
224.5	3605	22600
224.0	3701	22600

The discussion about the effect of the neighbor appliance will be divided into 4 parts based on the type of neighbor appliance.

A. Type 1 Appliance

The type 1 appliance has low power consumption and low internal impedance. The low-power consumption does not change the voltage level in the network, hence the disturbance produced by disturbance source (induction cooker A) will also be constant. The low internal impedance of type 1 appliance reduces the disturbance in the network. As shown in Figure 5.6, at disturbance frequency of 22800 Hz, the internal impedance of operation mode induction cooker A is 4.49 Ohm while the internal impedance of standby mode inverter microwave is 0.29 Ohm. Referring to Table 5.14, the type 1 appliance (standby mode inverter microwave) reduces the disturbance significantly by 93.6 %.

B. Type 2 Appliance

The type 2 appliance has low-power consumption and high internal impedance. The low-power consumption causes almost no additional voltage drop in the network and the high impedance is causing small impact to the disturbance appeared in the network. Since there is almost no additional voltage drop in the network, the disturbance generated by disturbance source appliance (induction cooker A) will be constant. Table 5.14 shows that type 2 neighbor appliances decrease the disturbances up to 13.6 % (Mixer) and increase the disturbances up to 13.7 % (PC). They can decrease or increase the disturbance due to the different properties of their internal impedance (inductive or capacitive). The testing is conducted in controlled high impedance network, so that even though the neighbor appliance like Notebook and PC have high internal impedance properties but the impedances are smaller than the impedance of controlled network, so that the effect seems to be significant. In the real network condition, the mains network normally has small impedance so that the effect of type 2 neighbor appliance will be less. The simulation of the effect of type 2 neighbor appliance to the disturbance in real mains network impedance can be seen in chapter 6.

C. Type 3 Appliance

The type 3 appliance which has low impedance and high-power consumption influences the disturbance through two ways. The first way, it provides low impedance which can filter and consequently reduce the disturbance. The second way it draws high current that is causing voltage drop and may change the disturbance produced by other appliances. In this testing, the operation mode of inverter microwave causes the mains voltage drop from 228.5 V to 225 V. Referring to Table 5.14, this drop voltage leads to change the disturbance produced by induction cooker A from 2.663 V to 3.550 V. Even though the disturbance produced by induction cooker A increases due to the mains voltage drop, but since the internal impedance of inverter microwave is very low at disturbance frequency, it consequently filters and reduces the disturbance significantly. The final disturbance in the network (decreasing or increasing the disturbance) is depending on the impact level of both properties (power consumption and internal impedance) to the disturbance. In this testing (inverter microwave as the neighbor appliance), the disturbance appeared in the network is decreased from 2.663 V to 0.565 V, meaning that the low internal impedance property has bigger impact to the disturbance in the network than the power consumption property.

D. Type 4 Appliance

The type 4 appliance has high internal impedance and high-power consumption. The high internal impedance will not give a significant effect to the disturbance while the high-power consumption causes the voltage drop and consequently change the disturbance produced by induction cooker A. In this testing, the operation of conventional microwave causes the voltage drops from 228.5 V to 224.5 V. This mains voltage drop increases the disturbance produced by induction cooker A from 2.664 V to 3.605 V. The testing result shows that the disturbance appeared in the network is increased from 2.663V to 3.477 V. The similar condition also occurs for the water cooker, the iron, and the hairdryer. The different effect to the disturbance is only caused by the difference of their internal impedances.

Based on the discussion of the effect of all neighbor appliances to the disturbance appeared in the network, it can be summarized as shown in Table 5.14.

Table 5.14 The effect of each type of appliances to the disturbance appeared in the network when induction cooker A is used as disturbance source

Neighbor Type	Neighbor Appliance		Effect to Disturbance		
			%Decrease	%Increase	
	Appliance	Mode	%	%	
Type 1	Inverter Microwave	Standby	93.1		Significantly Reduce
Type 2	Conv. Microwave	Standby		1.5	Slightly Increase /Decrease
	Mixer	Operation	13.6		
	Hand Blender	Operation	7.0		
	Personal Computer	Operation		13.7	
	TV LED	Operation	6.3		
	Notebook	Operation	8.9		
	Electric Massage	Operation		7.2	
	LED Lamp	Operation		6.1	
	CFL	Operation		1.9	
Type 3	Inverter Microwave	Operation	78.8		Significantly Reduce
Type 4	Conv. Microwave	Operation		30.6	Significantly Increase
	Water Cooker	Operation		17.7	
	Iron	Operation		18.3	
	Hairdryer	Operation		18	

Using the equivalent circuit of appliances and the disturbance characteristics, the testing scheme can be simulated. The simulation result of the disturbance appeared in the network and the percent error between the simulation and measurement can be seen in Table 5.15. It can be noticed that the disturbances obtained from the simulation are close to the disturbance obtained from the measurement.

Table 5.15 The comparison of disturbance occurred in the network between measurement and simulation when induction cooker A is used as disturbance source

Step	Disturbance Source		Neighbor		Disturbance		Error
					Measurement	Simulation	
	Appliance	Mode	Appliance	Mode	(Volt)	(Volt)	%
Step 1	Ind. Cooker A	ON	None		2.663		
Step 2	Ind. Cooker A	ON	Inv. Microwave	STB	0.183	0.189	3.5
Step 3	Ind. Cooker A	ON	Inv. Microwave	ON	0.565	0.545	3.5
Step 4	Ind. Cooker A	ON	Conv. Microwave	STB	2.704	2.576	4.7
Step 5	Ind. Cooker A	ON	Conv. Microwave	ON	3.477	3.537	1.7
Step 6	Ind. Cooker A	ON	Mixer	ON	2.300	2.324	1.1
Step 7	Ind. Cooker A	ON	Hand Blender	ON	2.476	2.440	1.5
Step 8	Ind. Cooker A	ON	Water Cooker	ON	3.136	3.216	2.6
Step 9	Ind. Cooker A	ON	PC	ON	3.027	2.978	1.6
Step 10	Ind. Cooker A	ON	TV LED	ON	2.496	2.564	2.7
Step 11	Ind. Cooker A	ON	Notebook	ON	2.427	2.442	0.6
Step 12	Ind. Cooker A	ON	Hairdryer	ON	3.142	3.092	1.6
Step 13	Ind. Cooker A	ON	Electric Massage	ON	2.856	2.746	3.8
Step 14	Ind. Cooker A	ON	Iron	ON	3.151	3.225	2.3
Step 15	Ind. Cooker A	ON	LED Lamp	ON	2.826	2.837	0.4
Step 16	Ind. Cooker A	ON	CFL	ON	2.715	2.747	1.2

By simulation, as can be seen in Table 5.16, the effect of each neighbor appliance properties (power consumption and internal impedance) can be identified separately. When operational inverter microwave is operated as the neighbor appliance (step 3), the power consumption of inverter microwave increases the disturbance of 33 % (from 2.663 V to 3.550 V), but the internal impedance of inverter microwave decreases the disturbance of 84 % (from 3.550 V to 0.565 V). The final disturbance occurred in the network is decreased 79 % (from 2.663 V to 0.565 V).

Table 5.16 The effect of power consumed and internal impedance of the neighbor appliance to the disturbance in the network produced by induction cooker A

Step	Neighbor Appliance		Power Consumption		Internal Impedance	
			V dist	%increase	V dist	%Decrease
	Appliance	Mode	(Volt)	%	(Volt)	%
Step 1	None		2.663			
Step 2	Inv. Microwave	STB	2.663	0	0.183	93
Step 3	Inv. Microwave	ON	3.550	33	0.565	84
Step 4	Conv. Microwave	STB	2.663	0	2.704	2
Step 5	Conv. Microwave	ON	3.605	35	3.477	4
Step 6	Mixer	ON	2.842	7	2.300	19
Step 7	Hand Blender	ON	2.663	0	2.476	7
Step 8	Water Cooker	ON	3.701	39	3.136	15
Step 9	PC	ON	2.842	7	3.027	7
Step 10	TV LED	ON	2.842	7	2.496	12
Step 11	Notebook	ON	2.663	0	2.427	9
Step 12	Hairdryer	ON	3.284	23	3.142	4
Step 13	Electric Massage	ON	2.842	7	2.856	1
Step 14	Iron	ON	3.701	39	3.151	15
Step 15	LED Lamp	ON	2.842	7	2.826	1
Step 16	CFL	ON	2.842	7	2.715	4

5.2.2 Induction Cooker B as Disturbance Source Appliance

The testing scheme is performed by operating induction cooker B as disturbance source appliance and other appliances as neighbor appliances. The induction cooker B has different internal impedance and disturbance properties compared with the induction cooker A, hence this testing is expected to complete the previous testing result. The initial mains voltage at no load condition was in between 230 V - 231 V. The testing steps of this scheme and the measurement result can be seen in Table 5.17.

According to Table 5.17, it can be noticed that the mains voltage varies during the test from 227.5 V to 224 V. To analyze the disturbance occurred in the network, the disturbances produced by induction cooker B for mains voltage level 227 V, 226 V, 224 V and 222 V should be defined. Using the similar testing method as explained in section 3.1, the disturbance produced by induction cooker B for those specific mains voltage levels can be known as shown in Table 5.18.

Table 5.17 The measurement result when induction cooker B is used as disturbance source

Step	Disturbance Source		Neighbor		V Mains	Disturbance
	Appliance	Mode	Appliance	Mode	(Volt)	(Volt)
Step 1	Ind. Cooker B	ON	None		227.5	0.187
Step 2	Ind. Cooker B	ON	Inv. Microwave	STB	227.5	0.094
Step 3	Ind. Cooker B	ON	Inv. Microwave	ON	224.0	0.141
Step 4	Ind. Cooker B	ON	Conv. Microwave	STB	227.0	0.195
Step 5	Ind. Cooker B	ON	Conv. Microwave	ON	224.0	0.209
Step 6	Ind. Cooker B	ON	Mixer	ON	227.0	0.187
Step 7	Ind. Cooker B	ON	Hand Blender	ON	227.0	0.186
Step 8	Ind. Cooker B	ON	Water Cooker	ON	224.0	0.207
Step 9	Ind. Cooker B	ON	PC	ON	227.0	0.196
Step 10	Ind. Cooker B	ON	TV LED	ON	227.0	0.194
Step 11	Ind. Cooker B	ON	Notebook	ON	227.5	0.185
Step 12	Ind. Cooker B	ON	Hairdryer	ON	225.0	0.204
Step 13	Ind. Cooker B	ON	Electric Massage	ON	227.0	0.194
Step 14	Ind. Cooker B	ON	Iron	ON	224.0	0.205
Step 15	Ind. Cooker B	ON	LED Lamp	ON	227.0	0.190
Step 16	Ind. Cooker B	ON	CFL	ON	227.0	0.197

Table 5.18 The disturbance produced by induction cooker B for mains voltage level within 224 V-227.5 V

Vmains	Disturbance	
	Level	Frequency
(V)	(mV)	(Hz)
227.5	187	22700
227.0	193	22600
225.0	200	22400
224.0	207	22300

A. Type 1 Appliance

The type 1 appliance has low-power consumption, consequently there is almost no additional voltage drop occurred in the mains network. Referring to Table 5.17, the type 1 appliance reduces the disturbance significantly from 0.187 V to 0.094 V (49 %).

B. Type 2 Appliance

The type 2 appliance has high impedance and low power consumption. The high impedance gives small impact to the disturbance in the network. The low power consumption does not change the mains voltage, hence the disturbance that is occurred in the network will not be changed significantly. According to Table 5.17, it can be noticed that the type 2 appliance only changes the small part of disturbance. They either slightly increase or decrease the disturbance.

C. Type 3 Appliance

The type 3 appliances influence the disturbance through two properties; low internal impedance and high-power consumption. The operation of inverter microwave causes the voltage drop from

227.5 V to 224 V. This mains voltage drop changes the disturbance produced by induction cooker B as disturbance source from 0.187 V to 0.207 V as can be seen in Table 5.17. Even though the disturbance produced by induction cooker B is increased due to the mains voltage drop, but since the internal impedance of inverter microwave is low at the disturbance frequency, it consequently filters and reduces the disturbance significantly. The final disturbance appeared in the network is depended on the impact level of each neighbor appliance properties to the disturbance. In this testing (step 3), the disturbance appeared in the network is decreased from 0.187 V to 0.141 V (reducing of 24,6 %), meaning that the low internal impedance of inverter microwave (0.92 Ohm) has more impact to the disturbance than the increase of disturbance due to the mains voltage drop (power consumption).

D. The Type 4 Appliances

The type 4 appliance which has high impedance and high-power consumption influences the disturbance due to the high-power consumption which is causing voltage drop and changes the disturbance produced by induction cooker B as the disturbance source appliance. In this testing, the operation of conventional microwave draws high current and drops the mains voltage from 227.5 V to 224 V. This mains voltage drop increases the disturbance produced by induction cooker B from 0.187 V to 0.207 V. In the other hand, the high internal impedance of conventional microwave gives almost no effect to the disturbance. The testing result shows that the disturbance appeared in the network is increased of 11.8 % from 0.187 V to 0.209 V.

The effect of neighbor appliances to the disturbance produced by induction cooker B can be summarized based on the type of appliances in Table 5.19 below.

Table 5.19 The effect of appliances to the disturbance (induction cooker B as disturbance source)

Neighbor Type	Neighbor Appliance		Effect to Disturbance		
			%Decrease	%Increase	
	Appliance	Mode	%	%	
Type 1	Inverter Microwave	Standby	49.7		Significantly Decrease
Type 2	Conv. Microwave	Standby		4.3	Slightly Increase /Decrease
	Mixer	Operation	0.0		
	Hand Blender	Operation	0.5		
	Personal Computer	Operation		4.8	
	TV LED	Operation	0.0		
	Notebook	Operation	1.1		
	Electric Massage	Operation		3.7	
	LED Lamp	Operation		1.6	
	CFL	Operation		5.3	
Type 3	Inverter Microwave	Operation	24.6		Significantly Decrease
Type 4	Conv. Microwave	Operation		11.8	Significantly Increase
	Water Cooker	Operation		10.7	
	Iron	Operation		9.6	
	Hairdryer	Operation		9	

The simulation result of the disturbance occurred in the network and the error difference between calculation and measurement can be seen in Table 5.20. It can be noticed that the disturbances gathered from the simulation are close to the disturbance obtained from the measurement.

Table 5.20 The comparison of disturbance between measurement and calculation when induction cooker B is used as disturbance source

Step	Disturbance Source		Neighbor		Disturbance		Error
					Measurement	Simulation	
	Appliance	Mode	Appliance	Mode	(Volt)	(Volt)	%
Step 1	Ind. Cooker B	ON	None				
Step 2	Ind. Cooker B	ON	Inv. Microwave	STB	0.094	0.097	3.2
Step 3	Ind. Cooker B	ON	Inv. Microwave	ON	0.141	0.145	2.8
Step 4	Ind. Cooker B	ON	Conv. Microwave	STB	0.195	0.193	1.0
Step 5	Ind. Cooker B	ON	Conv. Microwave	ON	0.209	0.207	1.0
Step 6	Ind. Cooker B	ON	Mixer	ON	0.187	0.188	0.5
Step 7	Ind. Cooker B	ON	Hand Blender	ON	0.186	0.191	2.7
Step 8	Ind. Cooker B	ON	Water Cooker	ON	0.207	0.206	0.5
Step 9	Ind. Cooker B	ON	PC	ON	0.196	0.195	0.5
Step 10	Ind. Cooker B	ON	TV LED	ON	0.194	0.192	1.0
Step 11	Ind. Cooker B	ON	Notebook	ON	0.185	0.186	0.5
Step 12	Ind. Cooker B	ON	Hairdryer	ON	0.204	0.200	2.0
Step 13	Ind. Cooker B	ON	Electric Massage	ON	0.194	0.192	1.0
Step 14	Ind. Cooker B	ON	Iron	ON	0.205	0.207	1.0
Step 15	Ind. Cooker B	ON	LED Lamp	ON	0.190	0.193	1.6
Step 16	Ind. Cooker B	ON	CFL	ON	0.197	0.193	2.0

Table 5.21 The effect of power consumption and internal impedance of the neighbor appliance to the disturbance in the network produced by induction cooker B

Step	Neighbor Appliance		Power Consumption		Internal Impedance	
			V dist	%increase	V dist	%Decrease
	Appliance	Mode	mV	%	mV	%
Step 1	None		0.187			
Step 2	Inv. Microwave	STB	0.187	0	0.094	50
Step 3	Inv. Microwave	ON	0.207	11	0.141	32
Step 4	Conv. Microwave	STB	0.193	3	0.195	1
Step 5	Conv. Microwave	ON	0.207	11	0.209	1
Step 6	Mixer	ON	0.193	3	0.187	3
Step 7	Hand Blender	ON	0.193	3	0.186	4
Step 8	Water Cooker	ON	0.207	11	0.207	0
Step 9	PC	ON	0.193	3	0.196	2
Step 10	TV LED	ON	0.193	3	0.194	1
Step 11	Notebook	ON	0.187	0	0.185	1
Step 12	Hairdryer	ON	0.200	7	0.204	2
Step 13	Electric Massage	ON	0.193	3	0.194	1
Step 14	Iron	ON	0.207	11	0.205	1
Step 15	LED Lamp	ON	0.193	3	0.190	2
Step 16	CFL	ON	0.193	3	0.197	2

By simulation, as can be seen in Table 5.21, the effect of each neighbor appliance properties (power consumption and internal impedance) can be identified separately. When operational inverter microwave is operated as the neighbor appliance (step 3), the power consumption of inverter microwave increases the disturbance of 11 % (from 0.187 V to 0.207 V), but the internal impedance of inverter microwave decreases the disturbance of 32 % (from 0.207 V to 0.141 V). The final disturbance decreases24 % (from 0.187 V to 0.141 V).

Referring to the testing result and discussion for this section, some characteristics related to the disturbance for simultaneous operation of appliances can be concluded as follows:

1. The neighbor appliances may affect the disturbance through two ways, providing low impedance path and changing the disturbance produced by the disturbance source.

    - **Providing low impedance path**
      Some appliances that are equipped with internal filter have low impedance in certain frequency range. This low internal impedance provides a good path for any signal or disturbance in the network, hence the disturbance appeared in the network could be filtered/reduced.
    - **Changing the disturbance produced by appliances**
      The appliances will draw current and may cause the voltage drop in the network. This voltage drop may lead to the change of disturbance produced by disturbance source appliance. If the disturbance source appliance has inverse correlation behavior between the produced disturbance and mains voltage level, then it will produce higher disturbance at lower mains voltage level. This condition consequently increases the disturbance appeared in the network.

2. Based on the internal impedance and power consumption properties, the neighbor appliances can be classified into 4 types. The effect of each type of appliances to the disturbance has been determined for two different disturbance source appliances; the induction cooker A and B. The summary of neighbor appliance classification can be seen in Table 5.22.

Table 5.22 The type of neighbor appliances and its effect to the disturbance appeared in the network

Nr.	CATEGORY	NEIGHBOR APPLIANCE TYPES			
		1	2	3	4
1	Power consumption	Low	Low	High	High
2	Internal Impedance at disturbance frequency	Low	High	Low	High
3	Causing Voltage Drop	No	No	Yes	Yes
4	Changing Distortion Produced	No	No	Yes	Yes
5	Shifting Disturbance Frequency	No	No	Yes	Yes
6	Affecting The Distortion	Significantly Decrease	Slightly Decrease/Increase	Significantly Decrease	Significantly Increase
7	Sample Appliances	Inv. Microwave STB	Conv Microwave STB Mixer, Handblender PC, TV, LED, CFL Notebook, Massage	Inv. Microwave ON	Conv Microwave ON Water Cooker Iron Hairdryer

3. The effect given by each neighbor appliance to the disturbance is unique and depended not only on the properties of neighbor appliance but also on the properties of distortion source appliance (internal impedance and disturbance behavior properties). This condition can be seen clearly in Table 5.23, when neighbor appliance type 1 and type 4 are operated simultaneously with induction cooker A and B as disturbance source.

Table 5.23 The disturbance for type 1 and type 4 of neighbor appliances

Neighbor Type	Disturbance Source		Neighbor		% Disturbance Change	
	Appliance	Mode	Appliance	Mode	Decrease	Increase
Type 1	Ind. Cooker A	ON	Inv. Microwave	STB	93.1	
	Ind. Cooker B	ON	Inv. Microwave	STB	49.7	
Type 4	Ind. Cooker A	ON	Conv. Microwave	ON		30.6
	Ind. Cooker B	ON	Conv. Microwave	ON		11.8

- At the first case, when neighbor appliance type 1 is connected, the disturbance reduction in induction cooker A (93 %) is higher than it is in induction cooker B (50 %). This is due to the internal impedance of operation mode of induction cooker B (0.39 ohm) which is lower than the internal impedance of operation mode induction cooker A (4.1 ohm), so that the effect of neighbor appliance to the disturbance will be less when induction cooker B is operated as disturbance source.
- At the second case, when neighbor appliance type 4 is connected, the increase of disturbance in induction cooker A (31 %) is higher than it is in induction cooker B (12 %). This is due to the difference of disturbance behavior of induction cooker A and B related to the mains voltage level variation. When the voltage drops, induction cooker A produces higher disturbance than induction cooker B.

4. The simulation of disturbance using the defined equivalent circuits for all testing schemes gives a close value to the disturbance obtained from the measurement. For the testing scheme of interaction between appliance at adjusted mains voltage, the maximum disturbance difference is 3.6 %. For the testing scheme of interaction between appliance at natural mains voltage, the maximum disturbance difference is 3.8%. Since the disturbance difference between measurement and simulation is relatively small, the equivalent circuit of appliance is sufficient to be used in the simulation of disturbance in residential network environment.

CHAPTER 6

SIMULATION OF DISTURBANCES IN A RESIDENTIAL NETWORK ENVIRONMENT

In a real residential network environment, some conditions which are normally occurring are the variation of mains voltage level, the presence of neighbor appliances and the variation of mains network impedance. Since the real network properties may vary over the time, the disturbance characteristics in the real network environment are difficult to be observed through direct test. The alternative method is by performing simulation to explore the disturbance characteristics occurred in residential network environment. The simulation can be used further to predict and investigate the disturbance characteristics occurred in the network. In the previous chapter, the properties and behavior of individual and simultaneous operation of appliances in controlled mains network have been defined and the equivalent circuit of appliances has been constructed. By referring the appliance equivalent circuit and applying some additional parameters representing the real residential network situation, the simulation of disturbance in residential network environment can be performed.

6.1. Simulation Parameters

In order to simulate the disturbances in residential network environment, some parameters and assumptions should be considered and applied in the simulation. Four parameters used in this simulation to approach the real residential situation are the mains network impedance, mains voltage level variation, the presence of neighbor appliances, and cable size-length variation used to connect the appliances. The list of parameters used in the simulation can be seen in Figure 6.1. Two parameters, the participating neighbor appliances and cable length connection, will be randomly configured using Monte-Carlo simulation to get a statistically-driven variation for the distribution of configuration. The parameter and assumption for these four parameters will be explained in the following sub-section.

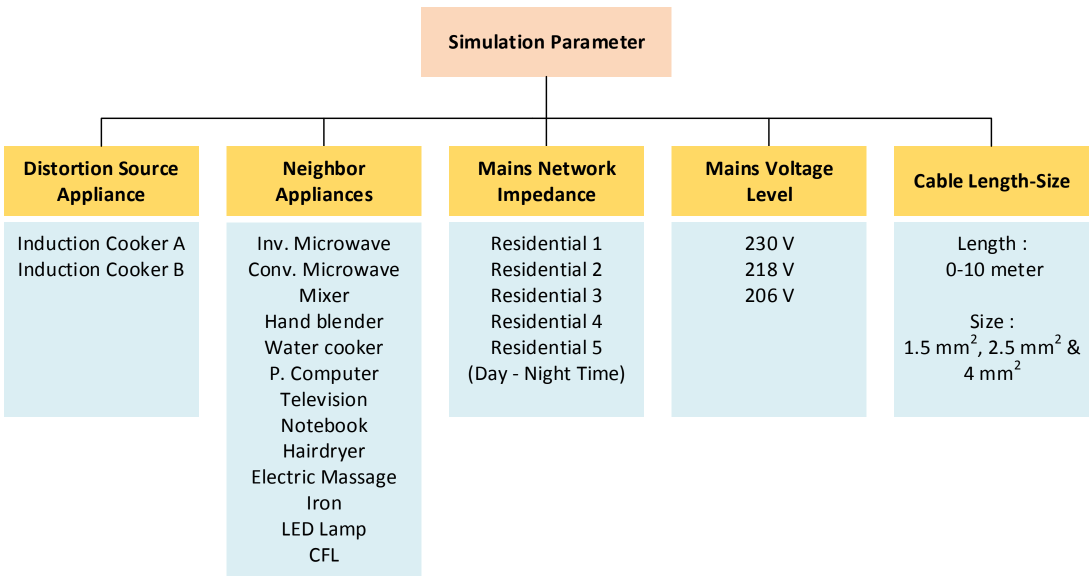


Figure 6.1 The parameters used in the simulation

6.1.1. Mains Network Impedance

In this simulation, 5 residential network impedances will be measured and taken as samples. The network impedance measurements are performed at two periods, daytime (low load period) and night time (peak load period). The testing scheme of mains network impedance measurement can be seen in Figure 6.2. After the mains network impedance properties are obtained, the equivalent circuit of mains network impedance is then defined and constructed for simulation purposes. The symbols used for each residential network are shown in Table 6.1.

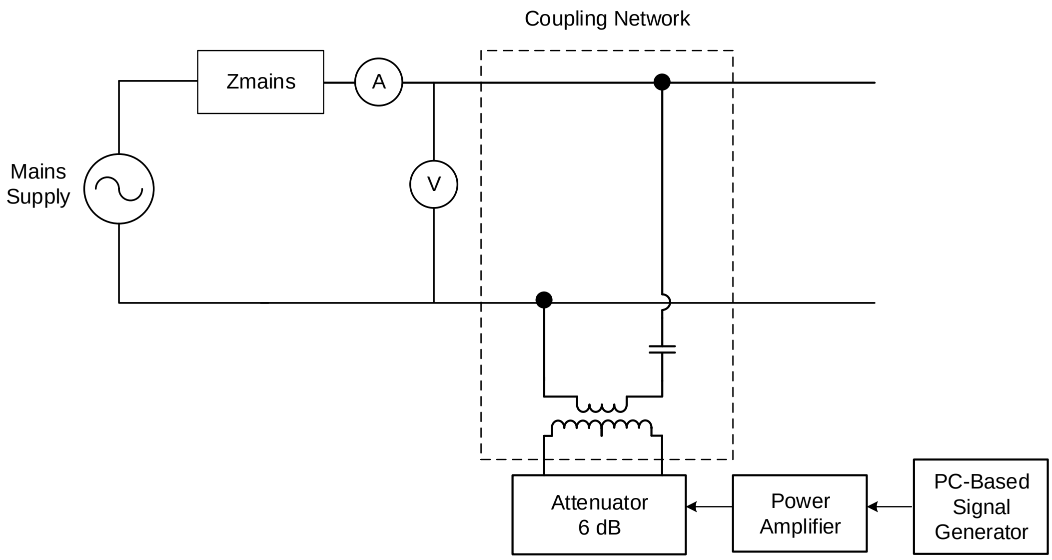


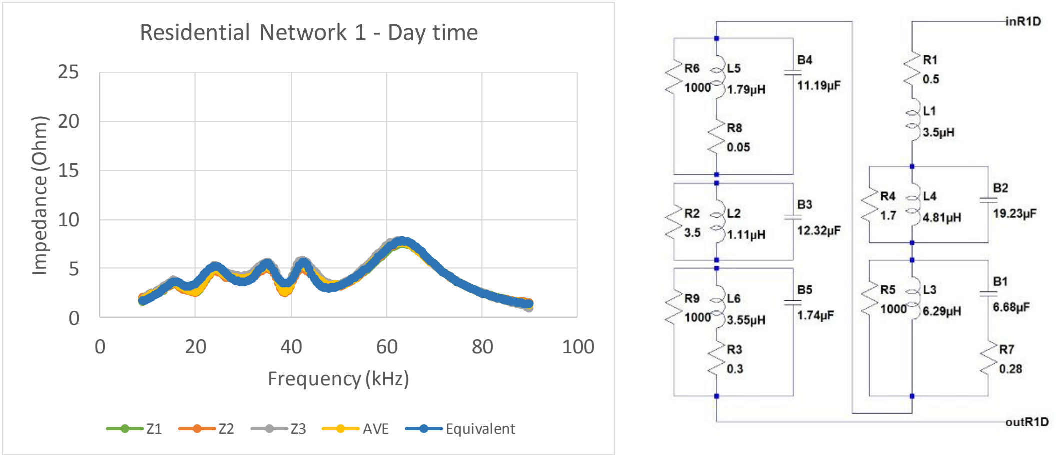
Figure 6.2 The testing scheme for measuring the mains network impedance

Table 6.1 The sample of residential network and symbols used in the simulation

No	Network	Symbol	
		Daytime	Nightime
1	Residential 1	R1D	R1N
2	Residential 2	R2D	R2N
3	Residential 3	R3D	R3N
4	Residential 4	R4D	R4N
5	Residential 5	R5D	R5N

A. Residential Network 1

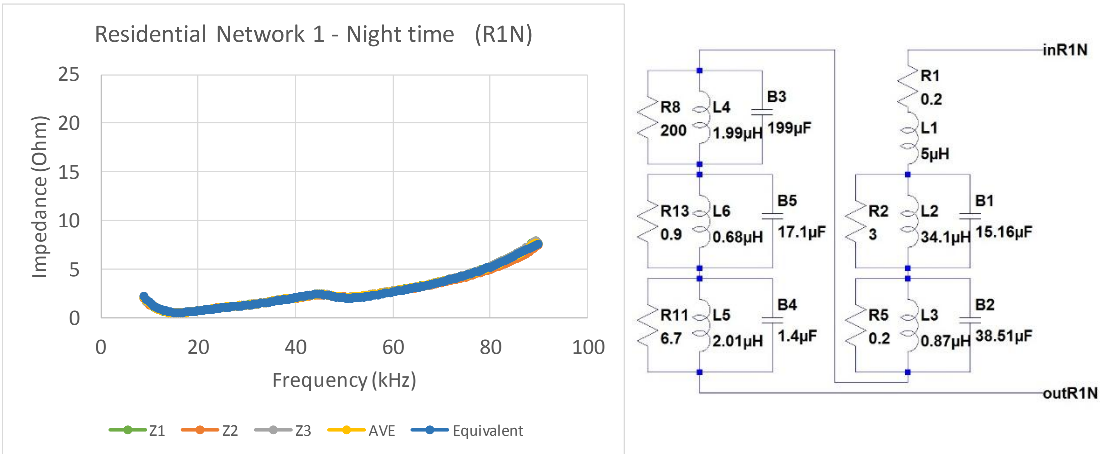
The impedance measurement of the first real residential network is performed at private apartment/house. The daytime network impedance was measured in between 09.00 - 10.00 AM. The measured network impedance for the day time can be seen in Figure 6.2(a). The curve Z1, Z2 and Z3 are the three measured network impedances at different time (5 seconds interval). It can be noticed that the impedance properties change every time as the consequence of the variation of the loads connected to the network. For the simulation purpose, the equivalent circuit of this residential mains network is defined and constructed as can be seen in Figure 6.2(b). The comparison between the measured network impedance (Z1, Z2 and Z3) and the equivalent network impedance (blue line) can be seen in Fig 6.3(a).



(a) (b)

Figure 6.3 The network impedance of residential network 1 at daytime period. (a) the impedance characteristics. (b) The impedance equivalent circuit

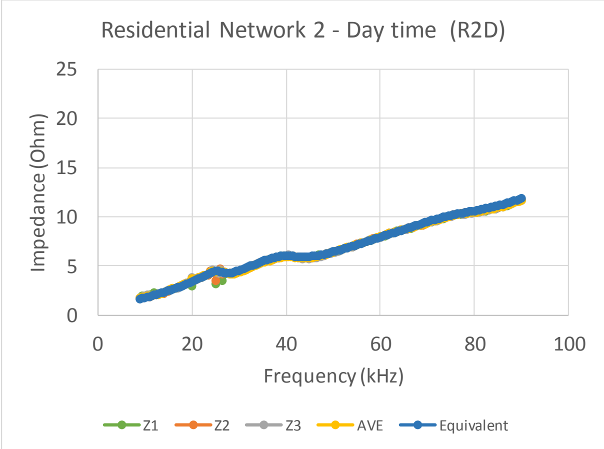
The night time of network impedance was measured in between 18.30 – 20.30 AM. The measured network impedance and the equivalent circuit can be seen in Figure 6.4. The mains network impedance and equivalent circuit for other 4 residential networks can be seen in Table 6.2.



(a) (b)

Figure 6.4 The network impedance of residential network 1 at night time period. (a) the impedance characteristics. (b) The impedance equivalent circuit

Table 6.2 The mains network impedances and equivalent circuits for residential network 2,3,4 and 5.

<table>
<tr><th>Mains Network</th><th>Impedance Value for Frequency Range 9-90 kHz</th><th>Impedance Equivalent Circuit</th></tr>
<tr><td>Residential Network 2 - Daytime</td><td>


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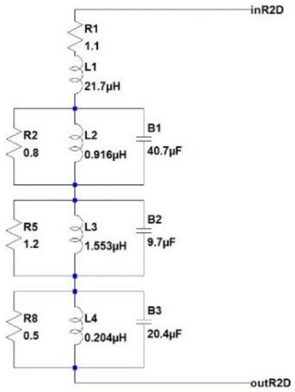
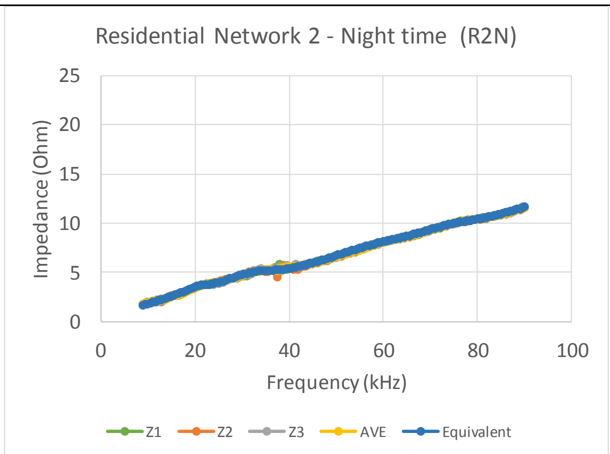


</td></tr>
<tr><td>Residential Network 2 - Night time</td><td>


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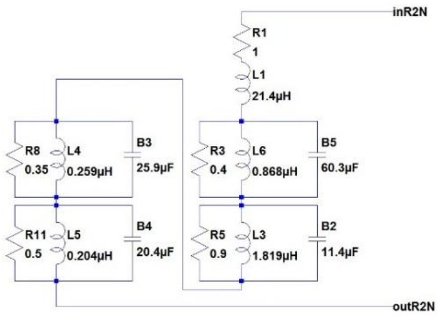
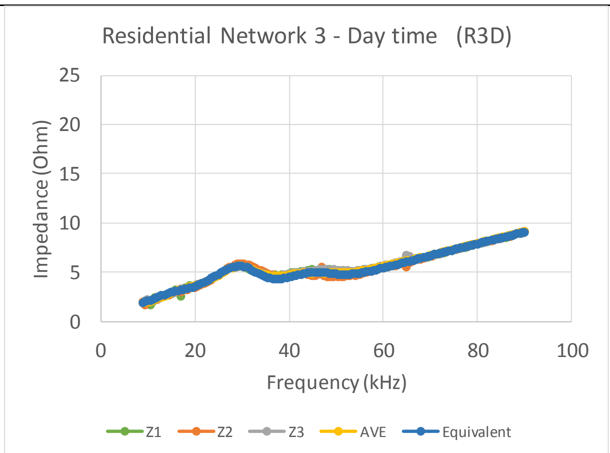


</td></tr>
<tr><td>Residential Network 3 - Daytime</td><td>


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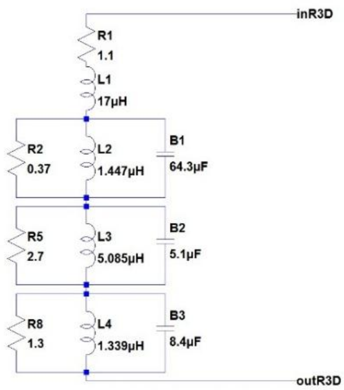

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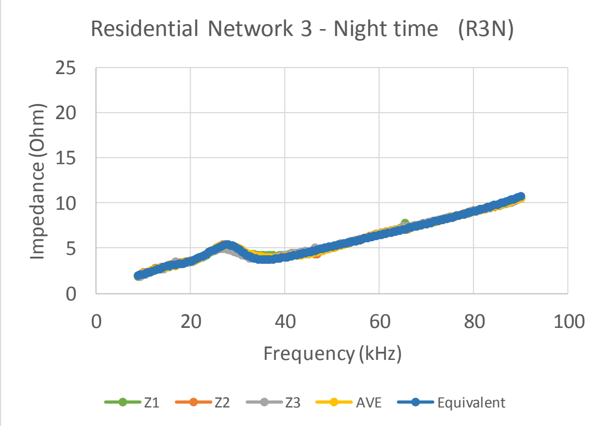
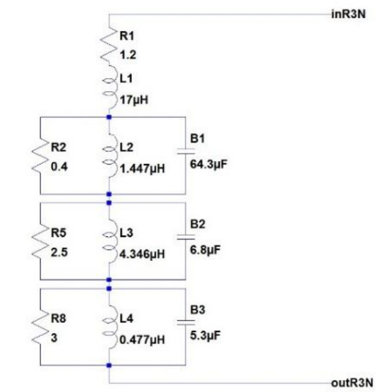
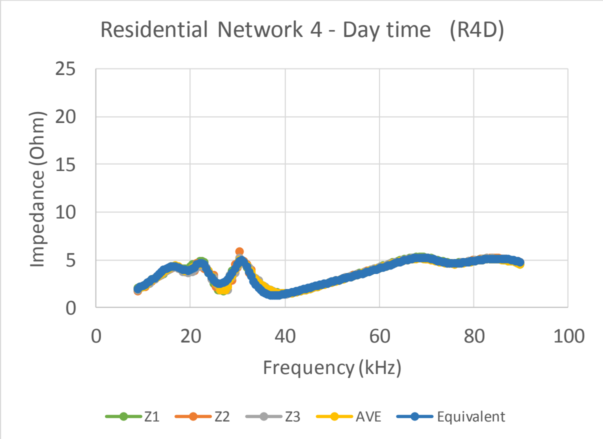
</table>

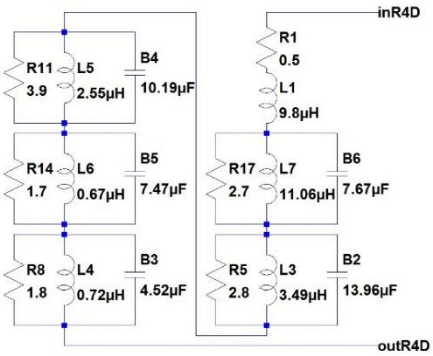
Residential Network 3 - Night time



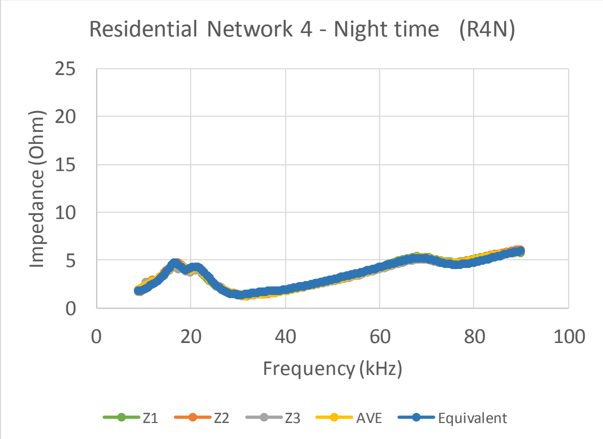


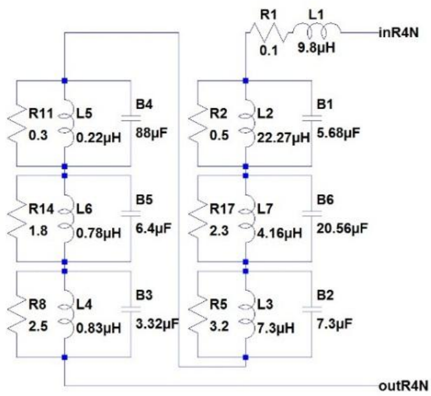
Residential Network 4 - Daytime



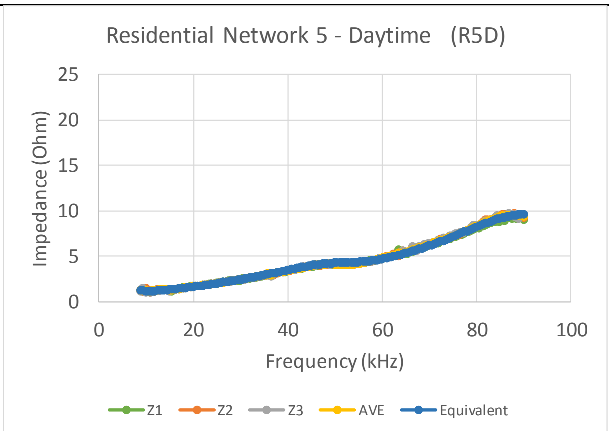


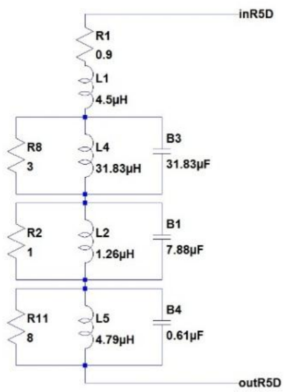
Residential Network 4 - Night time



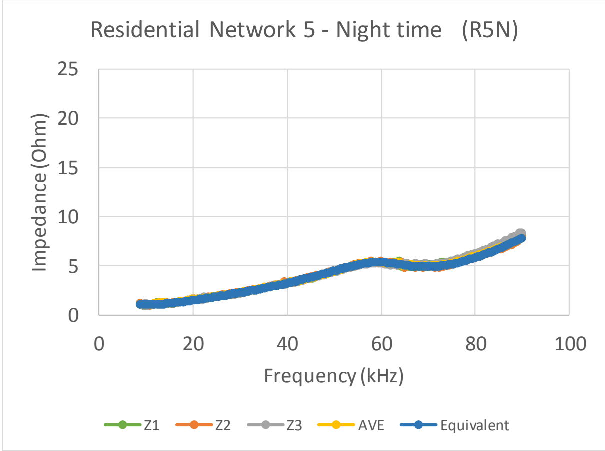


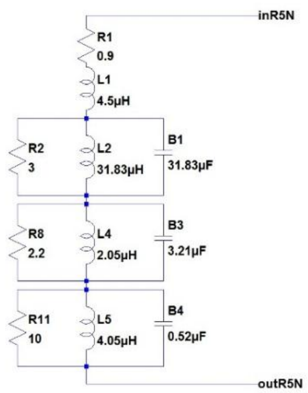
Residential Network 5 - Daytime





Residential Network 5 - Night time





6.1.2. Mains Voltage Level

Mains voltage level may influence the disturbance voltage produced by some household appliances as explained in chapter 3. The variation of mains voltage level may increase or decrease the disturbance produced by household appliances. The classification of disturbance behavior of appliances related to the mains voltage level can be seen in Table 3.2.

In the simulations, there are two mains voltage levels taken to observe the disturbance characteristics in the network. The first mains voltage level is 230 V to represent the nominal mains voltage level, while the second mains voltage level is the level which is causing the highest disturbance produced by the disturbance source appliances. The highest disturbance of induction cooker A is occurred at mains voltage of 218 V while for induction cooker B is occurred at mains voltage of 206 V. Hence, the mains voltage levels used for induction cooker A are 230 V and 218 V while for induction cooker B are 230 V and 206 V.

The voltage level is assumed in steady state condition after all participating appliances are connected to the network. According to the measurement result in chapter 3.1, the disturbance generated by induction cooker A and B for intended voltage level can be summarized in Table 6.3.

Table 6.3 The disturbance of induction cooker A and B for mains voltage level of 230 V, 218 V and 206 V

Nr.	Mains Voltage Level	Disturbance Level			
		Induction Cooker A		Induction Cooker B	
		Frequency	Voltage	Frequency	Voltage
	(V)	(Hz)	(V)	(Hz)	(V)
1	230	23100	2.255	22700	0.181
2	218	22300	4.151		
3	206			21100	0.282

6.1.3. Disturbance Source and Neighbor Appliances

The appliances used in the simulation will be divided into 2 groups, the disturbance source appliances and neighbor appliances. The disturbance source appliances used are induction cooker A and B, while the neighbor appliances used are inverter microwave, conventional microwave, mixer, hand blender, water cooker, personal computer, television, notebook, hairdryer, electric massage, iron, LED lamp and compact fluorescent lamp. The internal impedance of all appliances used in this simulation can be seen in Figure 5.7. The internal impedance equivalent circuit of each neighbor appliance can be found in chapter 4.

The neighbor appliances affect the disturbance through two properties; the power consumption and the internal impedance. In this simulation parameter, only the internal impedance properties of neighbor appliances will be considered, while the power consumption properties that may cause the voltage level variation is accommodated in mains voltage level variation parameter as mentioned in the previous sub-section.

6.1.4. Cable Length and Size Variation

The appliances are connected to the mains network through the power outlet installed in the building. Since the location of the power outlet depends on the design of the building, hence the distance of each power outlet to the point of common coupling (PCC) will vary. Moreover, the cable size and type used for connecting the power outlet to the PCC may also vary considering some factors including the current capacity utilization and the voltage drop in the cable.

In the previous section, the internal impedance properties for some household appliances has been identified. This impedance is measured when the appliances is directly connected to the mains network. The impedance properties will change when an additional extension cable is used for connecting the power outlet to the point of common coupling (PCC). As comparison, the impedance properties of induction cooker A for direct connection and with additional 1.5-meter extension cable are shown in Figure 6.5.

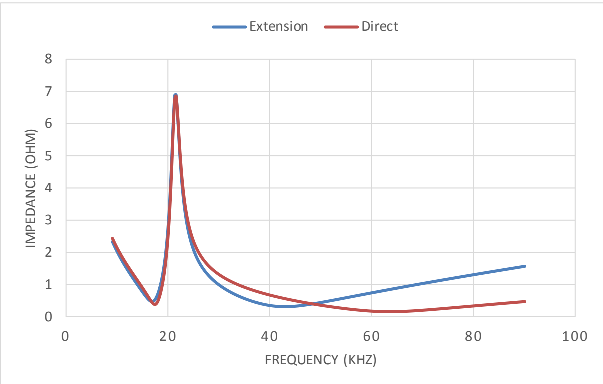


Figure 6.5 Impedance magnitude of induction cooker A for direct and with 1.5 m length cable extension connection

The cable used will change the impedance viewed at the point of common coupling. The addition of impedance is depending on the size, type and length of cable used. In this simulation, three sizes of cooper cable of 1.5 mm^2, 2.5 mm^2 and 4 mm^2 are used. The length of cable line from the power outlet to the power common coupling will be set from 0 m (direct connection) to 20 m.

Since the disturbance frequency that will be observed in this simulation is around 22 kHz, this will affect the effective resistance of the cable. Two effects, which affects the resistance of the cable at higher frequencies are skin effect and proximity effect. At higher frequency, the current tends to concentrate in the surface of the conductor known as skin effect. The skin effect yield to a rise of the effective resistance of the conductor with increasing frequency. The proximity effect also increases the effective resistance associated with the magnetic field of two conductors which are close together.

The AC resistance of conductor at higher frequency can be approximated by [29],

$$R_{\mathrm{ac}} = R_{\mathrm{dc}}(1 + \gamma_{\mathrm{s}} + \gamma_{\mathrm{p}}) \qquad (6.1)$$

Where,

R_{dc} = DC resistance at operating temperature (t)
γ_{s} = Skin effect factor
γ_{p} = Proximity effect factor

The skin effect factor (Ys) is given by the equation:

$$\gamma_{\mathrm{s}} = \frac{X_{\mathrm{s}}^{4}}{192 + 0.8X_{\mathrm{s}}^{4}}$$

Where,

$$X_{\mathrm{s}}^{2} = \frac{8\pi f k_s * 10^{-7}}{R_{\mathrm{dc}}}$$

f = frequency (Hz)
k_s = Skin effect coefficient (1 for round solid conductor)
R_{dc} = DC resistance at operating temperature (t)

The proximity effect factor (*Y*p) is given by the equation:

$$\gamma_{\mathrm{p}} = \frac{X_{\mathrm{p}}^{4}}{192 + 0.8X_{\mathrm{p}}^{4}}\left(\frac{D_c}{s}\right)^{2} \times 2.9$$

Where,

$$X_{\mathrm{p}}^{2} = \frac{8\pi f k_{\mathrm{p}} * 10^{-7}}{R_{\mathrm{dc}}}$$

f = frequency (Hz)
k_{p} = Proximity effect coefficient (1 for round solid conductor
R_{dc} = DC resistance at operating temperature (t)
D_{c} = Diameter of conductor (mm)
$s = Distance\ between\ conductor\ axis\ (mm)$

For single phase cable with round solid conductor, the skin effect and proximity effect factor at frequency 22 kHz and the cable impedance properties used in this simulation can be seen in Table 6.4. The capacitance of cable will be neglected since the cable length used (0-20 meter) in this simulation is relatively short.

Table 6.4 NYY Low voltage cable datasheet and the ac resistance at frequency 22 kHz (source: [30])

Nr.	Conductor Size	Rdc	Diameter (Dc)	Insulation Thikness	Distance (s)	Skin Effect	Proximity Effect
	mm^2	Ω/km	mm	mm	mm	γ s	γp
1	1.5	12.10	1.38	0.80	2.98	0.10	0.062
2	2.5	7.41	1.78	0.80	3.38	0.24	0.190
3	4	4.61	2.26	1.00	4.26	0.47	0.382

Nr.	Conductor Size	Rdc	Rac	Inductance
	mm^2	Ω/km	Ω/km	µH/km
1	1.5	12.1	14.1	343.0
2	2.5	7.41	10.6	317.0
3	4	4.61	8.5	316.0

6.2. Simulation Schemes

6.2.1. Effect of Mains Network and Mains Voltage Level

In this simulation scheme, the effect of mains network impedance and mains voltage level to the disturbance are observed. The simulation will be performed for 40 schemes related to the variable of disturbance source appliances (2 variables), mains network impedance (10 variables) and mains voltage level (2 variables). For each simulation scheme, 1000 combination operations of neighbor appliances and cable length will be applied. The parameter and the installation scheme can be seen in Figure 6.6 and 6.7.

Parameters		Items
Fixed Parameters	Disturbance Source	Induction Cooker A and B
	Cable Size	1.5 mm^2
Variable Parameters	Neighbor Appliance	All Neighbor Appliance
	Mains Network	R1D...R5D R1N...R5N
	Mains Voltage	230V, 218V, 206V
	Cable Length	0-20 meter

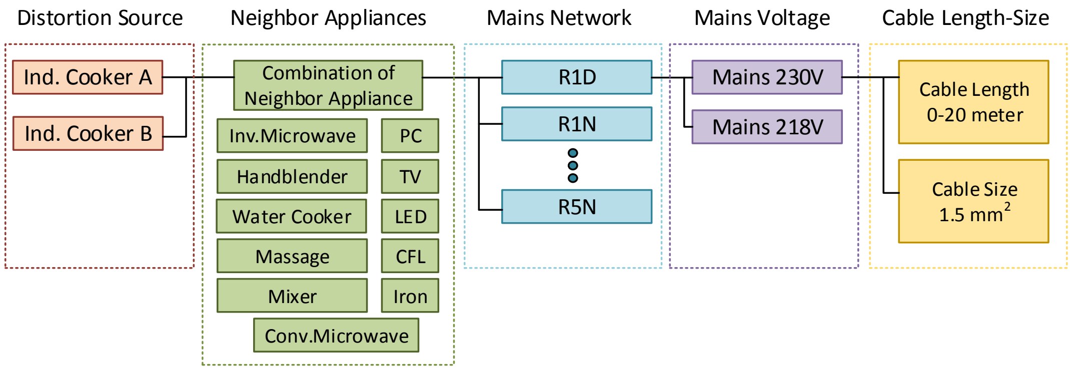


Figure 6.6 The parameter used in the simulation of disturbance in residential network environment

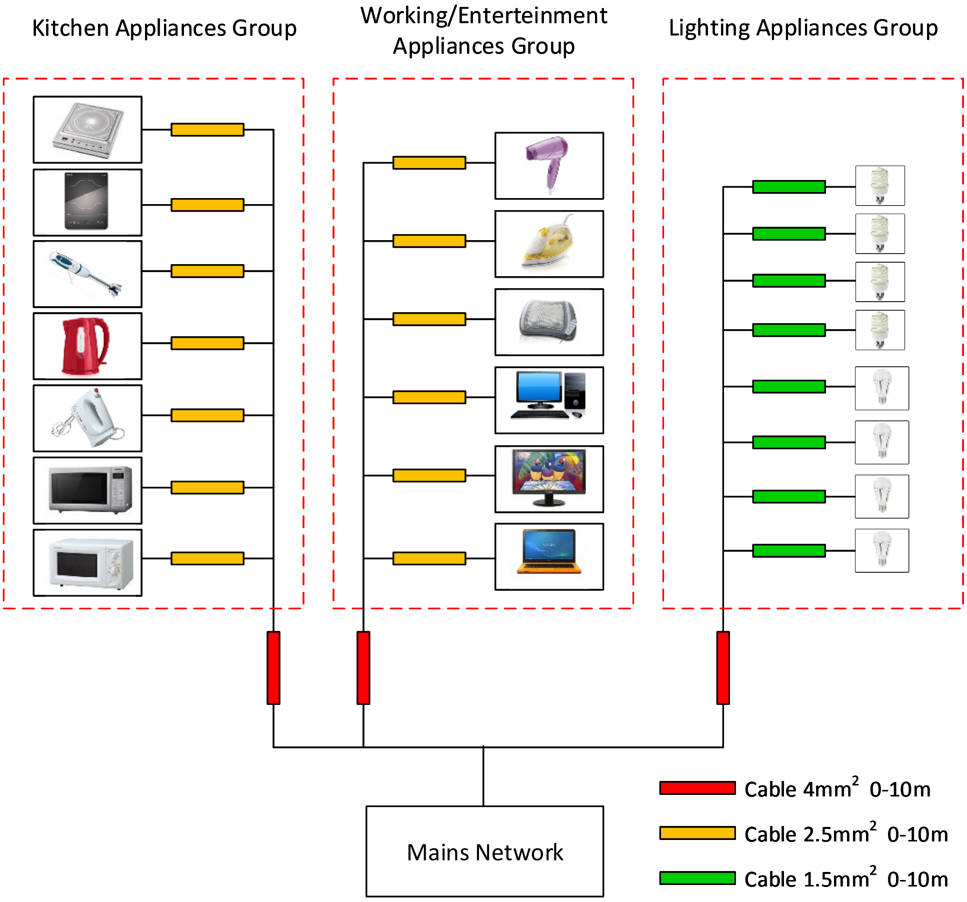


Figure 6.7 The installation scheme for the simulation of disturbance in residential network environment

6.2.2. The Effect of Individual Operation of Neighbor Appliances

The simulation in the previous scheme is performed by randomly operating the neighbor appliances simultaneously. To determine the effect of each neighbor appliance separately, the simulation will be performed by operating each neighbor appliance individually at specific network parameter as shown in Figure 6.8. The simulation configuration can be seen in Fig 6.9. In this simulation, the disturbance source appliance is induction cooker A connected to the residential network 1 at mains voltage level of 230 V. The cable size used is 1.5 mm^2 and the cable length will be randomly configured 1000 times within 0-20 meter of length.

Parameters		Items
Fixed Parameters	Disturbance Source	Induction Cooker A and B
	Mains Network	R1 Daytime Ntework
	Mains Voltage	230 Volt
	Cable Size	1.5 mm^2
Variable Parameters	Neighbor Appliance	All Neighbor Appliance
	Cable Length	0-20 meter

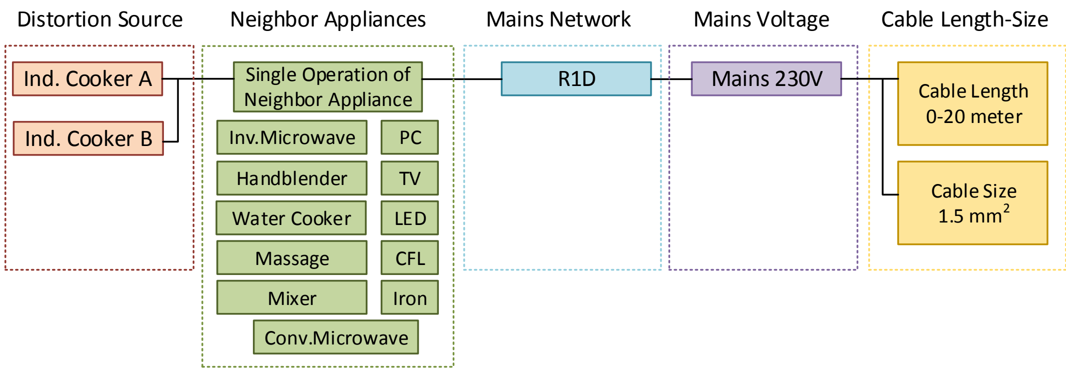


Figure 6.8 The simulation schemes for neighbor appliances effect

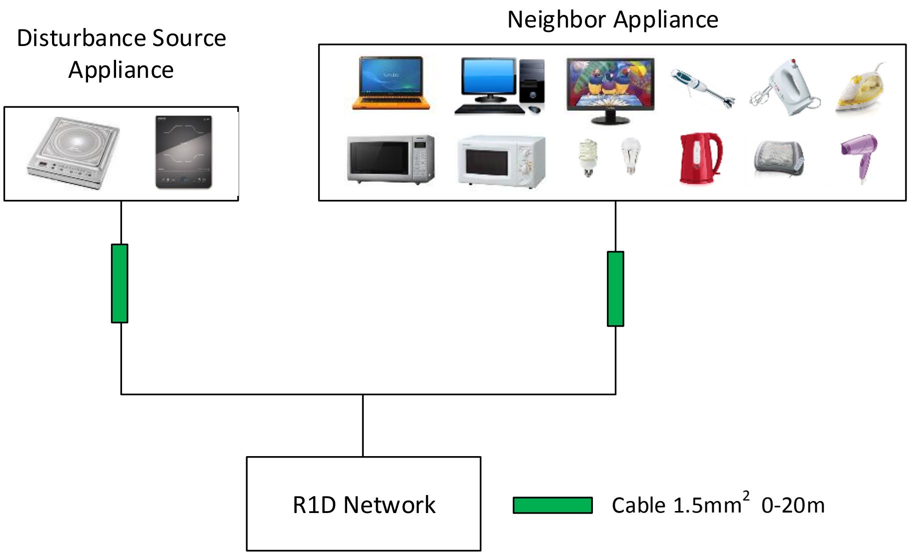


Figure 6.9 The installation scheme for the simulation of the effect of individual neighbor appliance to the disturbance in residential network environment

6.2.3. The Effect of Cable Size-Length Configuration

To observe the effect of cable length and size, the simulation is conducted at specific network parameters and participating appliances using different cable sizes and lengths as can be shown in Figure 6.10. The simulation configuration can be seen in Fig 6.11. The inverter microwave is used as neighbor appliance. The cable sizes used are 1.5 mm^2 and 4 $mm^{2,}$ while the cable length will be 1000 times randomly configured within 0-20 meter of length.

Parameters		Items
Fixed Parameters	Disturbance Source	Induction Cooker B
	Neighbor Appliance	Inverter Microwave
	Mains Network	R2 Daytime Ntework
	Mains Voltage	230 Volt
Variable Parameters	Cable Length	0-20 meter
	Cable Size	1.5 mm^2, 2.5 mm^2, 4 mm^2

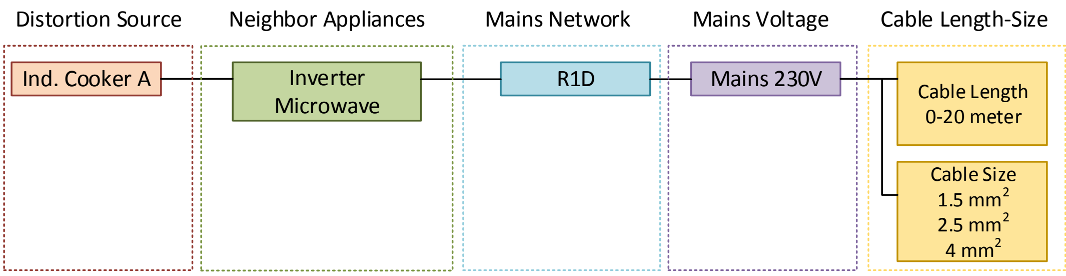


Figure 6.10 The simulation schemes for cable size-length effect

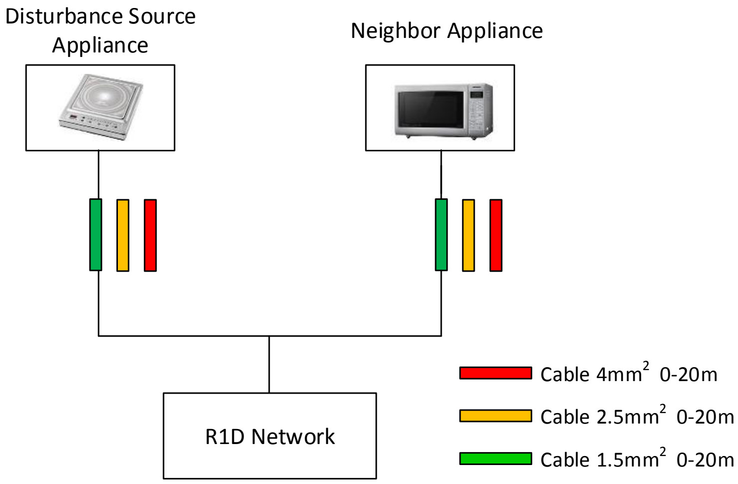


Figure 6.11 The installation scheme for the simulation of the effect of cable size-length to the disturbance in residential network environment

6.3. Simulation Result and Discussion

The simulation results of disturbance properties in residential network environment can be seen in Table 6.5. The Table shows the minimum and maximum values of the disturbances at different mains network impedances and mains voltage levels. The minimum value is the average of the 100 lowest disturbance values while the maximum value is the average of the 100 highest disturbance values obtained from the simulation. It can be noticed that generally the disturbances are affected by the network parameters used. Table 6.5 shows that the disturbances have a different minimum and maximum value for each mains network and mains voltage level. This condition occurs for both disturbance source appliances induction cooker A and B. The effect each of network parameter is explained in the following subsection.

Table 6.5 The simulation of disturbance result for induction cooker A as the disturbance source appliance

Nr.	Mains Network	Induction Cooker A				Induction Cooker B			
		Mains 230V		Mains 218V		Mains 230V		Mains 206V	
		Disturbance Level		Disturbance Level		Disturbance Level		Disturbance Level	
		Min (V)	Max(V)	Min (V)	Max(V)	Min (V)	Max(V)	Min (V)	Max(V)
1	**R1D**	0.085	1.175	0.164	1.939	0.084	0.171	0.128	0.262
2	**R1N**	0.058	0.543	0.109	0.737	0.054	0.149	0.083	0.229
3	**R2D**	0.082	1.312	0.158	2.016	0.082	0.172	0.126	0.265
4	**R2N**	0.081	1.230	0.157	1.914	0.081	0.171	0.127	0.263
5	**R3D**	0.082	1.269	0.159	1.978	0.082	0.172	0.127	0.264
6	**R3N**	0.082	1.233	0.159	1.927	0.082	0.171	0.127	0.263
7	**R4D**	0.086	0.993	0.165	1.795	0.087	0.171	0.132	0.259
8	**R4N**	0.088	0.885	0.167	1.678	0.090	0.173	0.134	0.259
9	**R5D**	0.070	0.784	0.134	1.148	0.067	0.160	0.106	0.248
10	**R5N**	0.069	0.782	0.134	1.141	0.067	0.160	0.105	0.248

6.3.1. The Effect of Mains Network Impedance

The mains network impedance affects the disturbances appearing in the network. Some characteristics obtained from the simulation results are as follows:

- The mains network influences the minimum and maximum disturbance level occurred in the network as can be seen in Table 6.5. The difference of maximum disturbance between mains networks is significant for induction cooker A as the disturbance source. At mains voltage 230 V, the difference between maximum disturbance (1.326 V) and minimum disturbance (0.536 V) reaches 60%.

- Table 6.5 also shows the maximum disturbance that is possible entering the mains network for different mains network impedances. For induction cooker A at mains voltage of 230 V, the maximum possible disturbance is 1.326 V (at R2D network). Compared to the disturbance source of induction cooker A at 230 V (2.254 V), the maximum disturbance that is possible to enter the mains network is 59 %.

- The disturbance distribution probability for each mains network can be seen in Figures 6.12 and 6.13. It can be noticed that the disturbance distributions are significantly different for each mains network. For induction cooker A, the highest spread level of disturbance distribution is occurred at R2D network while the lowest spread level is occurred at R1N network. For induction cooker B, the spread level of disturbance distribution for different mains network is almost similar. Generally, the mains network gives different effect to the spread level of disturbance distribution produced by induction cooker A and B due to the differences of their internal impedance properties.

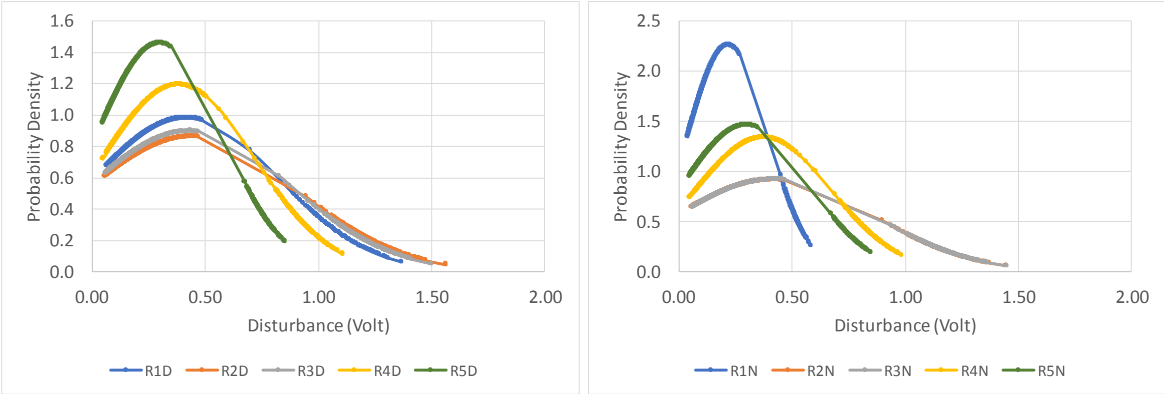


Figure 6.12 The probability density of disturbance distribution for induction cooker A at different mains networks

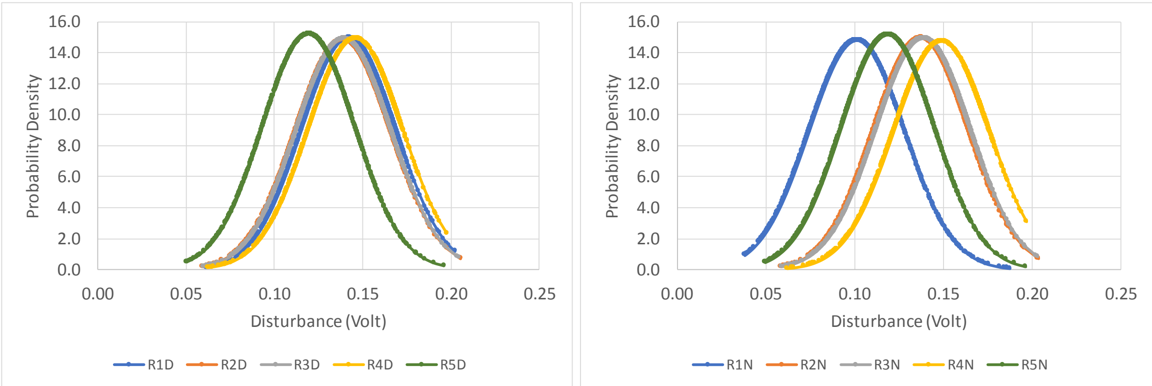


Figure 6.13 The probability density of disturbance distribution for induction cooker B at different mains networks

In real network environment, the mains network impedance affects the disturbance occurred in the network. For some disturbance source appliances, the variation of mains network impedance may give a significant effect depending on the internal impedance of the disturbance source appliance.

6.3.2. Effect of Mains Voltage Level Variation

Referring to the simulation results in Table 6.5, the maximum disturbance occurred in the network is higher for lower mains voltage levels. The mains voltage level changes both properties the level and frequency of disturbance produced by induction cooker A and B. The change of the disturbance level will consequently change the disturbance level appearing in the network. Besides, the change of disturbance frequency may also change the impedance value of mains network and internal impedance of appliance that eventually may also change the disturbance appearing in the network. These conditions are indicated by the variation of disturbance level occurred in the network for different mains voltage levels.

Figures 6.14 and 6.15 show more clearly the probability density of disturbance distribution curve for induction cooker A and B as the disturbance source appliances. It can be noticed that the disturbance at mains voltage 218 V (orange line) has a higher maximum value and is spreading widely than the disturbance at nominal voltage 230 V (blue line). The effect of mains voltage level which is causing higher disturbance at lower mains voltage level is similar for both disturbance sources appliances the induction cooker A and B. This is due to the similar disturbance behavior of induction cooker A and B which are producing higher disturbance level at lower mains voltage level.

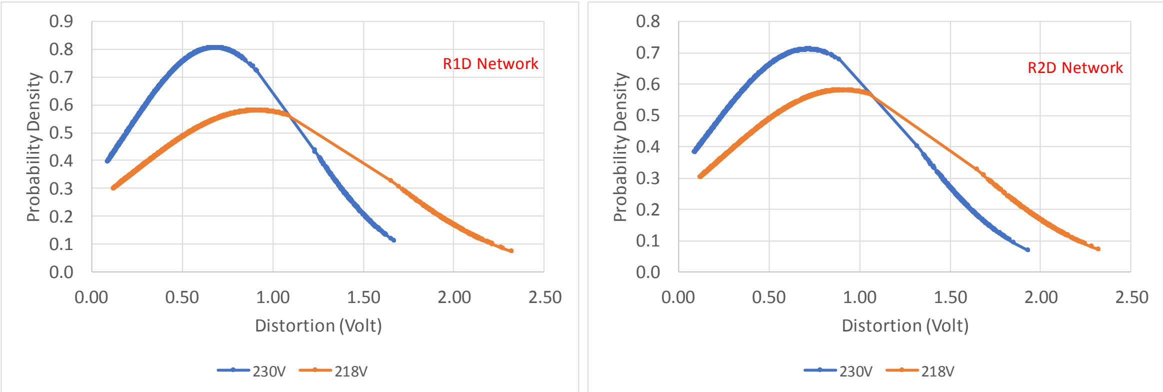


Figure 6.14 The probability density of disturbance distribution for induction cooker A at 230V and 218V

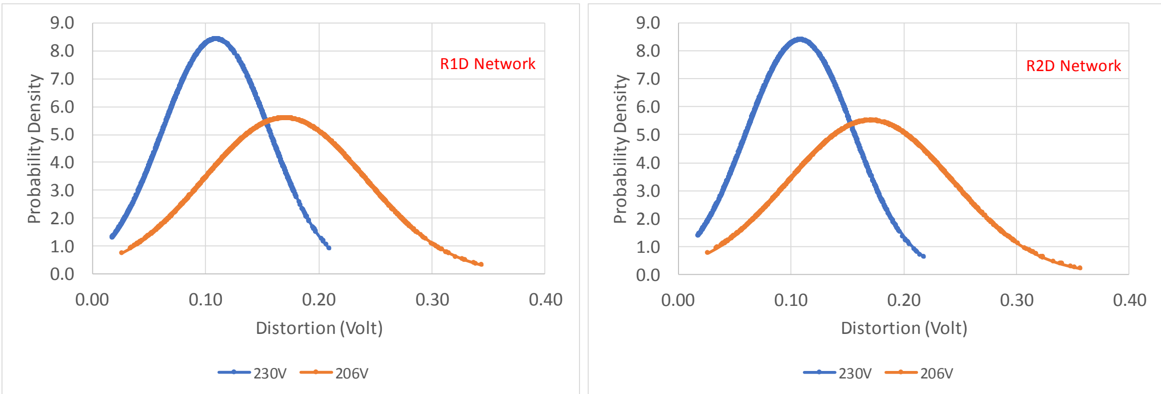


Figure 6.15 The probability density of disturbance distribution for induction cooker B at 230V and 206V

6.3.3. The Effect of Neighbor Appliances

Table 6.6 shows the disturbance in the network when induction cooker A is operated simultaneously with neighbor appliance at mains voltage of 230 V in daytime residential 2 network (R2D). It can be noticed that each neighbor appliance gives different effect to the disturbance in the network. The effect of the neighbor appliance in this simulation is only regarding the internal impedance property.

The neighbor appliance can be divided into 2 groups, the first group are the neighbor appliances that reduce the disturbance significantly and the second group are the neighbor appliances that reduce the disturbance slightly. The appliances classified into the first group are inverter microwave in both standby and operation modes, while the rest of appliances are classified into the second group. The probability density of disturbance distribution curve for each single neighbor appliance can be seen in Figure 6.16. It can be noticed that when induction cooker A is operated as disturbance source, all neighbor appliances always reduce the disturbance appearing in the network. Another characteristic obtained from this simulation is that each neighbor appliance combining with the cable length configuration causes different spread level of disturbance distribution curve.

Table 6.6 Effect of neighbor appliance to the disturbance produced by induction cooker A when they are connected in daytime residential 2 network (R2D) at mains voltage of 230 V

Nr.	Symbol	Neighbor Appliance	V Distortion		% Reduction
			Min (V)	Max (V)	Max (%)
1	A	None	1.473	1.766	
2	B	Inv. Microwave STB	0.190	0.753	57.3
3	C	Inv. Microwave ON	0.296	0.610	65.5
4	D	Conv. Microwave STB	1.488	1.762	0.2
5	E	Conv. Microwave ON	1.489	1.760	0.3
6	F	Mixer	1.552	1.740	1.5
7	G	Hand blender	1.502	1.741	1.4
8	H	Watercooker	1.426	1.694	4.1
9	I	Personal Computer ON	1.426	1.694	4.1
10	J	Television LED ON	1.440	1.663	5.8
11	K	Notebook ON	1.399	1.618	8.4
12	L	Hairdryer	1.404	1.640	7.1
13	M	Massage	1.487	1.746	1.1
14	N	Iron	1.345	1.548	12.4
15	O	LED Lamp ON	1.478	1.749	1.0
16	P	CFL Lamp ON	1.430	1.677	5.0

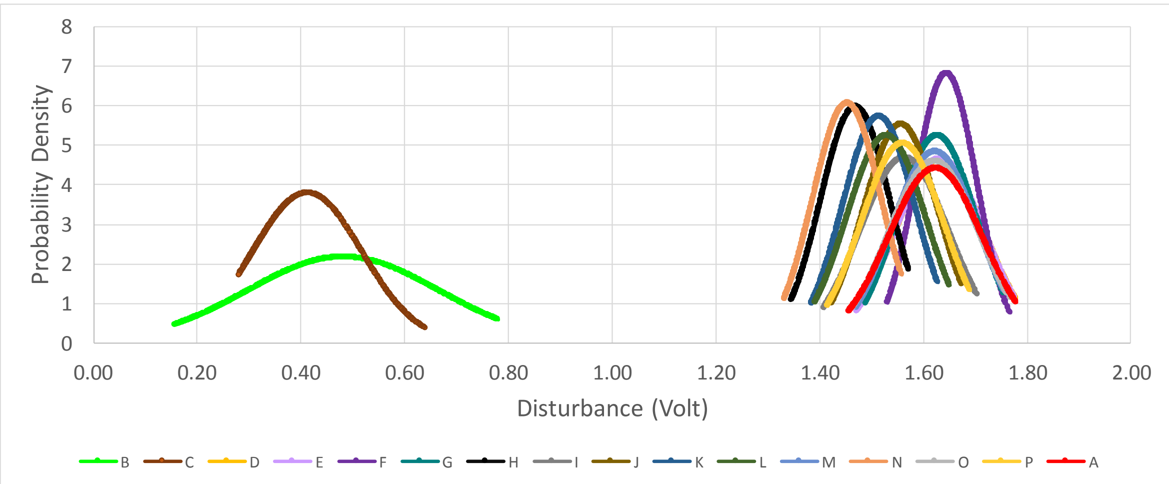


Figure 6.16 The distribution curve of disturbance produced by induction cooker A when each neighbor appliance is connected in daytime residential 1 network (R2D) at mains voltage of 230V

Figure 6.17. shows the disturbance in the network for random combination operation of all neighbor appliances at mains voltage of 230V in different mains networks. Compared to the disturbance produced by induction cooker A at mains voltage 230V (the red line), it can be noticed that the simultaneous combination operations of neighbor appliances always reduce the disturbance appearing in the network.

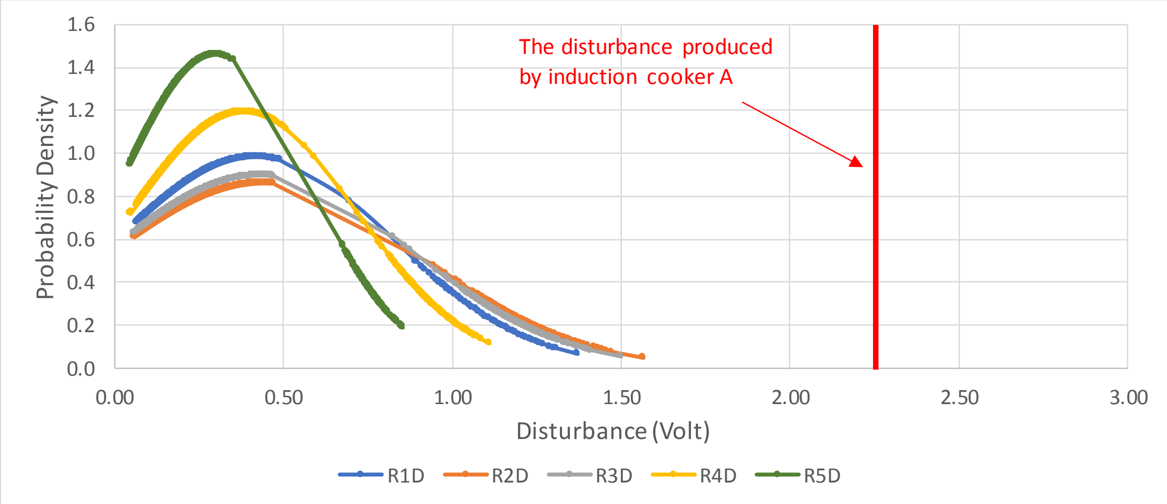


Figure 6.17 The distribution curve of disturbance produced by induction cooker A when random combinations of neighbor appliances are connected to the network at mains voltage of 230V

When induction cooker B is operated as the disturbance source, the effect of neighbor appliance to the disturbance can be seen in Table 6.7. It is shown that each neighbor appliance gives different effect to the disturbance in the network. The interesting result obtained from the simulation is that inverter microwave at certain cable length configuration may increase the disturbance in the network. Figure 6.18 shows clearly the probability density of disturbance distribution curve for each single neighbor appliance.

Table 6.7 The Effect of neighbor appliance to the disturbance produced by induction cooker B when they are operated in daytime residential 2 network (R2D) at mains voltage 230 V

Nr.	**Symbol**	**Neighbor Appliance**	**V Distortion**		**% Decrease**	**% Increase**
			Min (V)	**Max (V)**	**Max (%)**	**Max (%)**
1	A	None	0.126	0.192		
2	B	Inv. Microwave STB	0.028	0.220		14.7
3	C	Inv. Microwave ON	0.054	0.205		7.0
4	D	Conv. Microwave STB	0.128	0.191	0.4	
5	E	Conv. Microwave ON	0.128	0.191	0.3	
6	F	Mixer	0.141	0.186	3.2	
7	G	Hand blender	0.132	0.189	1.5	
8	H	Watercooker	0.124	0.191	0.6	
9	I	Personal Computer ON	0.123	0.193	0.8	
10	J	Television LED ON	0.129	0.189	1.3	
11	K	Notebook ON	0.126	0.190	1.0	
12	L	Hairdryer	0.125	0.191	0.2	
13	M	Massage	0.129	0.190	0.8	
14	N	Iron	0.123	0.191	0.4	
15	O	LED Lamp ON	0.128	0.191	0.3	
16	P	CFL Lamp ON	0.126	0.191	0.5	

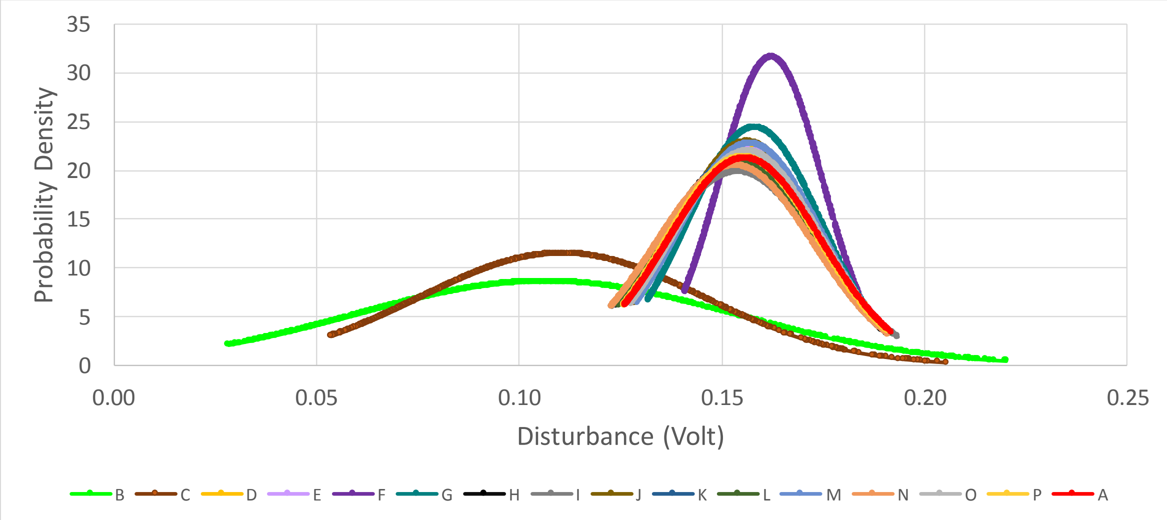


Figure 6.18 The distribution curve of disturbance produced by induction cooker B when each neighbor appliance is connected in daytime residential 1 network (R2D) at mains voltage of 230 V

Referring to Figure 6.18, when the induction cooker B is operated as disturbance source, most of appliance when operated as single neighbor appliance reduces the disturbance appearing in the network. But there is neighbor appliance, the inverter microwave, which for some certain cable length configurations may increase the disturbance occurred in the network. The effect of randomly combined operation of all neighbor appliances to the disturbance is shown in Figure 6.19. At certain appliance combinations and cable length configurations, the maximum disturbance occurred in the network is higher than the disturbance produced by individual operation of induction cooker B (red line). This condition occurs for all samples of mains network impedances.

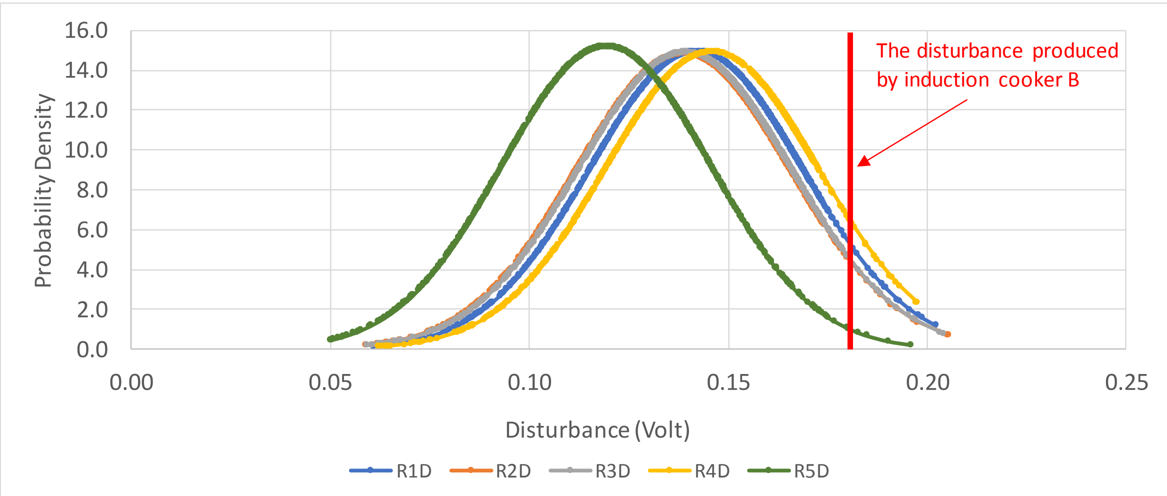


Figure 6.19 The distribution curve of disturbance produced by induction cooker B when random combinations of neighbor appliances are connected to the network at mains voltage of 230V

According to the disturbance simulation result in the real network environment, it can be concluded that the presence of neighbor appliance generally reduces the disturbance in the network, but the reduction level of each neighbor appliance is different from each other. When low impedance appliance is not available in one customer network, a large portion of disturbance could enter the distribution network.

6.3.4. The Effect of Cable Connection

The cable length and size variations cause the change of the impedance properties which may affect to the disturbance in the network. Figure 6.20 shows three disturbances occurred in the network when induction cooker B is connected to the R2D network. The first (blue line) is the disturbance distribution curve when induction cooker B and inverter microwave are connected to the network using different cable length configurations. The second (orange line) is the disturbance when induction cooker B and inverter microwave are connected directly to the network, and the third (red line) is the internal disturbance produced by individual operation of induction cooker B. According to Fig 6.20, some effect of cable length to the disturbance occurred in the network can be summarized as follows:

- The variation of cable length configuration of appliances causes the possible disturbance spreads from the minimum to the maximum level. It can be noticed by comparing the disturbance between direct connection (orange line) and using cable connection (blue line).
- For certain disturbance source appliances, the presence of specific neighbor appliance with certain cable length configurations can cause the increase of disturbance in the network. It can be noticed from Figure 6.20 that the disturbance levels for simultaneous operation of induction cooker B and inverter microwave (blue line) at specific cable length configurations are higher than the disturbance source of individual operation of induction cooker B (red line).

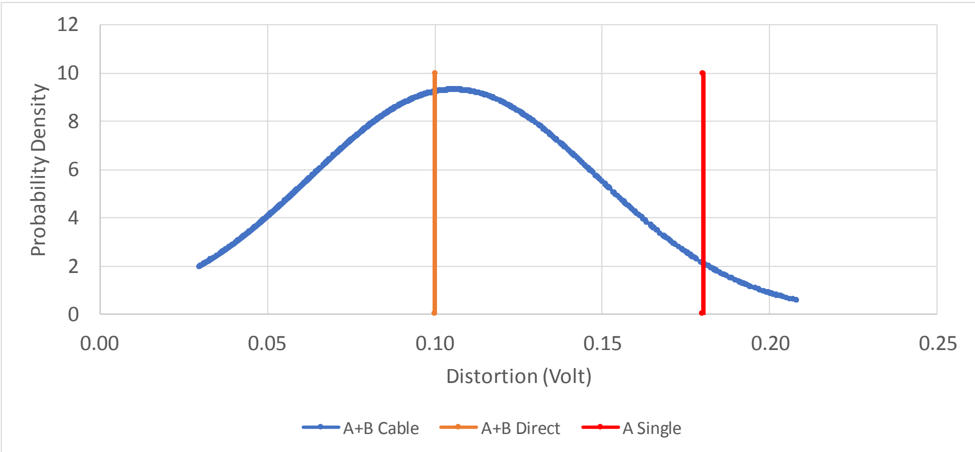


Figure 6.20 The effect of cable length configuration to the disturbance when induction cooker B and inverter microwave are connected to the network

Regarding the cable size variation, Figure 6.21 shows the disturbance occurred in the network when induction cooker A and B are operated in R1D network at mains voltage 230 V using 3 different cable sizes of 1.5 mm^2, 2.5 mm^2, and 4 mm2. It can be noticed that the cable size variation does not cause significant effect to the disturbances appearing in the network. This is due to the small inductance differences among cable size of 1.5 mm^2, 2.5 mm^2, and 4 mm^2.

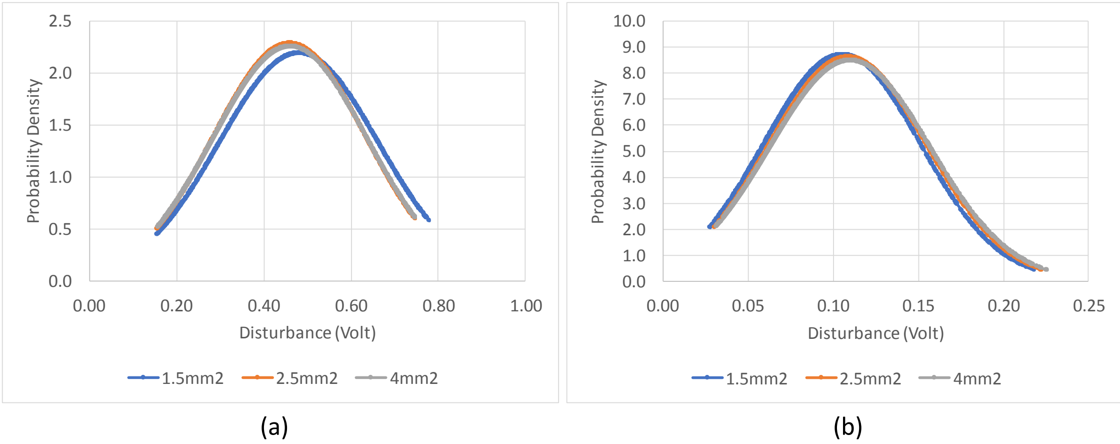


Figure 6.21 The effect of cable size configuration to the disturbance occurred in the network for different disturbance source appliance. (a) Induction cooker A, (b) Induction cooker B

CHAPTER 7
EVALUATION OF THE EXISTING STANDARD EMISSION TEST PROCEDURE

The existing conducted emission test defined in the common EMC standards based on operating the appliance individually at nominal voltage level in artificial mains network (AMN) can be seen in Fig 7.1. The artificial mains network (AMN) that is used in emission test for frequency range 9 kHz to 150 kHz, according to the standard [19], has an impedance characteristic of 50 Ω // (50 µH + 5 Ω). The actual emission when the appliances are operated in the real network condition could be different due to the influence of some factors in the network environment.

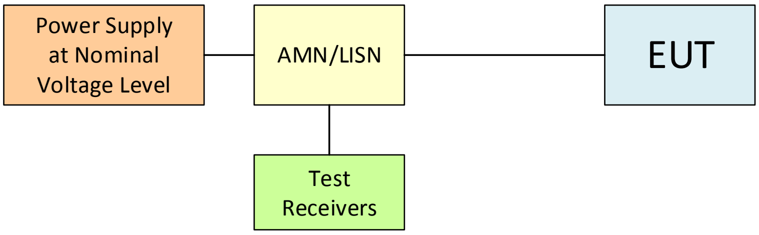


Figure 7.1 The conducted emission test scheme

The emission test is expected to obtain the highest possible disturbance level produced by the equipment under test. It can be inferred from the instruction stated in the standard that during the test, the level of disturbance produced by the equipment under test shall be maximized by varying the configuration (cable layout, operational state) of the equipment [11]. In case of the induction cooker as the EUT which has several power level options, the emission test procedure indicates that the test should be performed when it is operated at certain power level option which is producing the highest disturbance.

The measurements and simulations presented in this thesis indicate some situations of existing conducted emission test procedures which may lead to a difference of disturbance obtained between standard emission test procedure and real network situation. The user should consider and be aware that there are situations in which the emission occurred in the field could be different. The evaluations of the standard emission test procedure are discussed in the following section.

7.1. Conducted Emission Test at Nominal Voltage Level

Regarding to the voltage level supplied to the equipment under test, the existing emission test procedure only requires the test at the nominal voltage level [11]. Other standard regulates the supply voltage level tolerance of ±10 % to the nominal voltage in public distribution system [15]. Concerning the mains voltage level variation, the disturbance produced by some appliances may be affected by the supply voltage variation. Hence, the highest disturbance produced by the appliances could occur at different voltage levels and consequently the emission test at nominal voltage level may not provide the highest possible disturbance produced by the EUT.

Referring to Figure 3.4, Figure 3.7 and Table 3.1, it can be noticed that the disturbances produced by some household appliances are affected by the supply voltage level. For the appliances that are classified into type 2, 3, and 4 (see Table 3.2), the disturbance produced by the appliance at the nominal voltage (230 V) could be either lower or higher than it is produced at other voltage levels in the range within 239 V - 206 V. The comparison between the disturbance produced at nominal voltage level and the highest disturbance for each household appliance can be seen in Table 7.1.

Table 7.1 The comparison between the highest disturbance produced by appliance and the disturbance produced by appliance at nominal voltage level

Nr.	Equipment Under Test	Distortion	Highest Distortion		Difference
		Vmains 230V	Distortion	Vmains	
		(mV)	(mV)	(V)	(%)
1	Induction Cooker A	2254.5	4151.4	218	84
2	Induction Cooker B	181.2	281.9	206	56
3	Inverter Microwave	547.8	662.0	206	21
4	Conventional Microwave	15.0	24.1	206	60
5	Mixer	18.7	23.4	212	25
6	Hand blender	25	31	239	24
7	Personal Computer	31.1	37.9	206	22
8	Television (LED)	26.6	27.5	224	3
9	Notebook	85.7	86.1	215	0
10	Hair dryer	44.9	45.1	233	0
11	Electric Massage	51.1	51.1	230	0
12	LED Lamp	7.9	8.4	206	6
13	Compact Fluorescent Lamp	16.0	17.4	230	8

Table 7.1 shows that for some appliances, the highest disturbance in the frequency range 9 kHz to 150 kHz is not occurring at nominal voltage level of 230 V. Most of appliances produce the highest disturbance at lower supply voltage level. For example, the highest disturbance produced by induction cooker A is at supply voltage level of 218 V. The difference of disturbance produced at the nominal voltage (2.255 V) and the highest disturbance (4.151 V) is 84 %. Since the emission test is expected to obtain the highest possible disturbance produced by equipment under test, the effect of supply voltage level should be considered when performing the emission test.

There are two types of measuring receiver that can be used in the conducted emission test, modern time domain (FFT-based) test receivers and conventional stepped frequency scan receivers. The implementation of emission test for varied voltage levels will give a different impact to each measurement receiver regarding the testing time.

For modern FFT-based receivers, the commonly conducted emission test can be performed very quickly since the FFT-based receivers can reduce the testing time significantly [21]. The emission test provider then can use the gained time to perform further conducted emission investigation for different supply voltage levels (the voltage variation test systems can refer to the IEC 61000-4-11 standard).

For conventional stepped frequency scan test receivers, the emission test for varied supply voltage levels will be time consuming (increase the testing time significantly) and consequently impact to the testing cost/fee. To minimize those deficiencies, the emission test (for varied supply voltage level) can be selected to be performed only for certain predefined conditions. The considerations in selecting the EUT for further investigation are based on some facts of disturbance properties obtained from measurement and simulation as follows:

- The effect of supply voltage level to the disturbance produced is detected for frequency range 9 kHz to 150 kHz.
- The difference between the disturbance produced at nominal voltage and the highest disturbance is lower than two times (see Table 7.1). The highest difference of disturbance occurred for induction cooker A (84 %).
- The disturbance level produced by the EUT that have high difference of disturbance for different supply voltage levels is not always critical. For example, the conventional microwave which has 60% disturbance difference is only producing the highest disturbance of 24.1 mV (87 dBuV) which is still much lower than the permitted emission limit (110 dBuV).

By referring the facts of disturbance above, further assessment (the emission test at varied supply voltage level) could be limited to be performed only for EUT that produce the disturbance higher than a half of maximum permitted emission (110 dBμV – 6 dBμV = 104 dBμV) at nominal voltage level (230V) and the test only for conducted emission in the frequency range 9 kHz to 150 kHz.

The recommended steps related to the implementation of varied voltage levels on conducted emission test for conventional frequency domain test receiver are as follows (see Figure 7.2):

1. Performing regular conducted emission test for frequency range 9 kHz to 150 kHz (at the nominal voltage level).
2. Evaluating the emission level in the frequency range 9 kHz to 150 kHz. If the emission level is higher than 104 dBμV, further assessment (the emission test at varied supply voltage level) is recommended to be performed. Otherwise, the emission test is completed.
3. Identifying the supply voltage level that is causing the highest disturbance produced by the EUT. It can be determined by adjusting the voltage level (the voltage variation test system can refer to IEC 61000-4-11 standard) and performing time domain measurement using regular oscilloscope or an FFT-based measurement receiver. By the FFT function, the supply voltage level causing the highest disturbance can be identified quickly.
4. After the mains voltage level that is causing the highest disturbance is defined, the conducted emission test for frequency range 9 kHz to 150 kHz is performed for that defined voltage level (which is causing the highest disturbance).

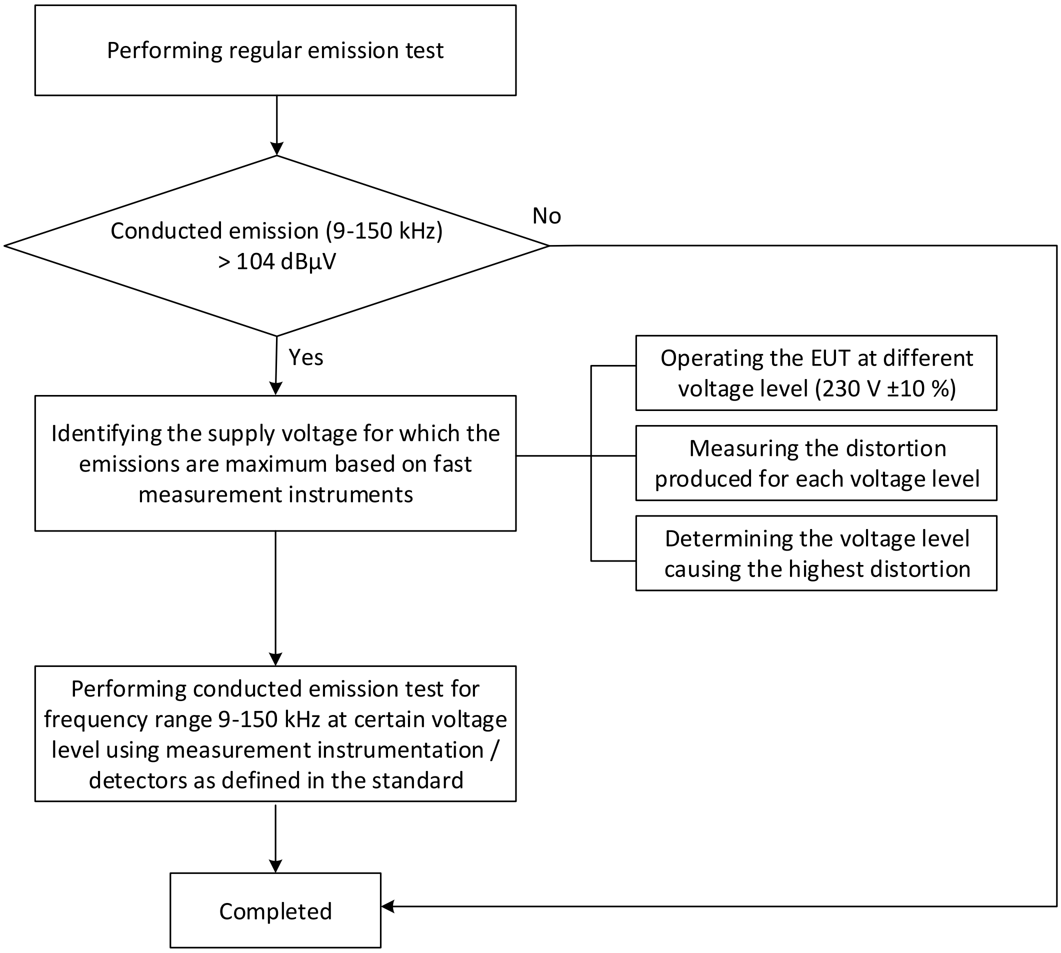


Figure 7.2 The flow chart for the emission test using conventional test receiver related to the supply voltage level variation.

7.2. The Presence of Neighbor Appliance and Variation of Network Impedance

The existing standard emission test arranges the EUT to be operated individually and connected to the artificial mains network (AMN). Since in the real situation many appliances can be connected to the network simultaneously and the mains network impedance may also vary, the disturbance occurred in the real network may be higher than it is measured in the existing standard emission test configuration. The simulations of disturbance occurred in the network when the disturbance source appliance is operated simultaneously with neighbor appliances and connected to some real residential networks have been conducted in chapter 6.

Referring to Figure 6.2, 6.3 and Table 6.2, it can be noticed that for frequency range within 9-90 kHz, the impedance values of AMN (50 Ω // (50 µH + 5 Ω)) are always higher than the impedance values of all real network samples as can be seen in Figure 7.3. Besides, the impedances of AMN always have inductive behavior for all frequency range while the impedances of the real networks have not only inductive but also capacitive behavior for certain frequency ranges. These different impedance characteristics may affect the disturbance occurred in the network.

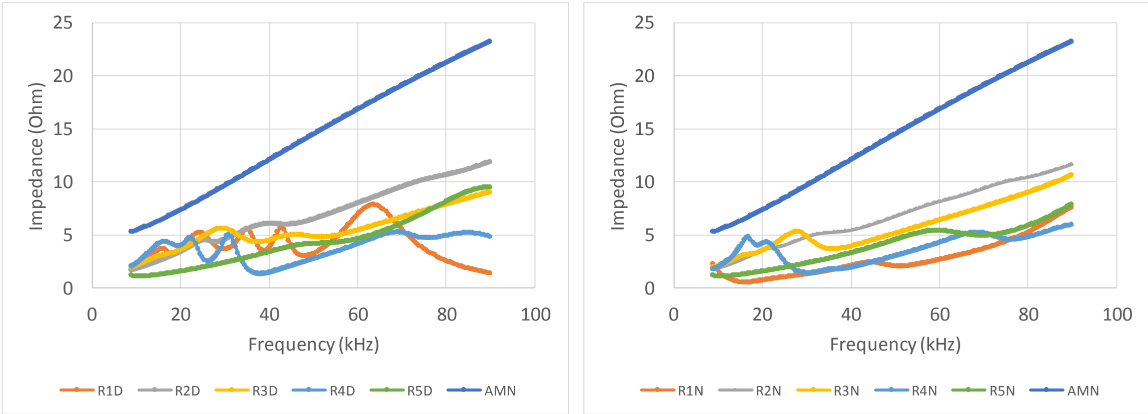


Figure 7.3 The internal impedance comparison between AMN and some real residential network.

The discussion in this subsection is only focused on the effect of neighbor appliances and network impedance variation to the disturbance by comparing the disturbance properties obtained using existing emission test configuration (the EUT operated individually and connected to AMN) and the real network condition (the EUT and random combination of neighbor appliances are operated simultaneously and connected to 5 samples of residential networks). The simulation results can be seen in Table 7.2.

Regarding to the simulation results obtained for both disturbance source appliances (induction cooker A and B), the disturbances occurred in the real residential network condition at nominal voltage level (230 V) are always smaller than the disturbance obtained in standard test configuration. But when the mains voltage level is not 230 V due to the voltage drop in the network, the disturbance that occurs in the real residential network condition could be higher than it is obtained in the standard test configuration. To overcome this issue, finding the highest possible disturbance by adjusting the supply voltage level is necessary as it is recommended in section 7.1.

Table 7.2 The disturbance occurred in the network when the induction cooker A is operated as the disturbance source appliances

Nr.	Mains Network	Induction Cooker A		Induction Cooker B	
		Disturbance		Disturbance	
		Mains 230V	Mains 218V	Mains 230V	Mains 206V
		Max(V)	Max(V)	Max(V)	Max(V)
1	**Test Standard**	**1.970**		**0.183**	
2	**R1D**	1.175	1.939	0.171	0.262
3	**R1N**	0.543	0.737	0.149	0.229
4	**R2D**	1.312	2.016	0.172	0.265
5	**R2N**	1.230	1.914	0.171	0.263
6	**R3D**	1.269	1.978	0.172	0.264
7	**R3N**	1.233	1.927	0.171	0.263
8	**R4D**	0.993	1.795	0.171	0.259
9	**R4N**	0.885	1.678	0.173	0.259
10	**R5D**	0.784	1.148	0.160	0.248
11	**R5N**	0.782	1.141	0.160	0.248

When the highest disturbance can be obtained at the emission test, the voltage variation due to the operation of neighbor appliances may not lead to higher disturbance occurred in the network than it is obtained from the emission test. The result also indicates that the artificial mains network is still sufficient to represent the mains network impedance.

7.3. The Existing Standards are not Covering all Household Appliances

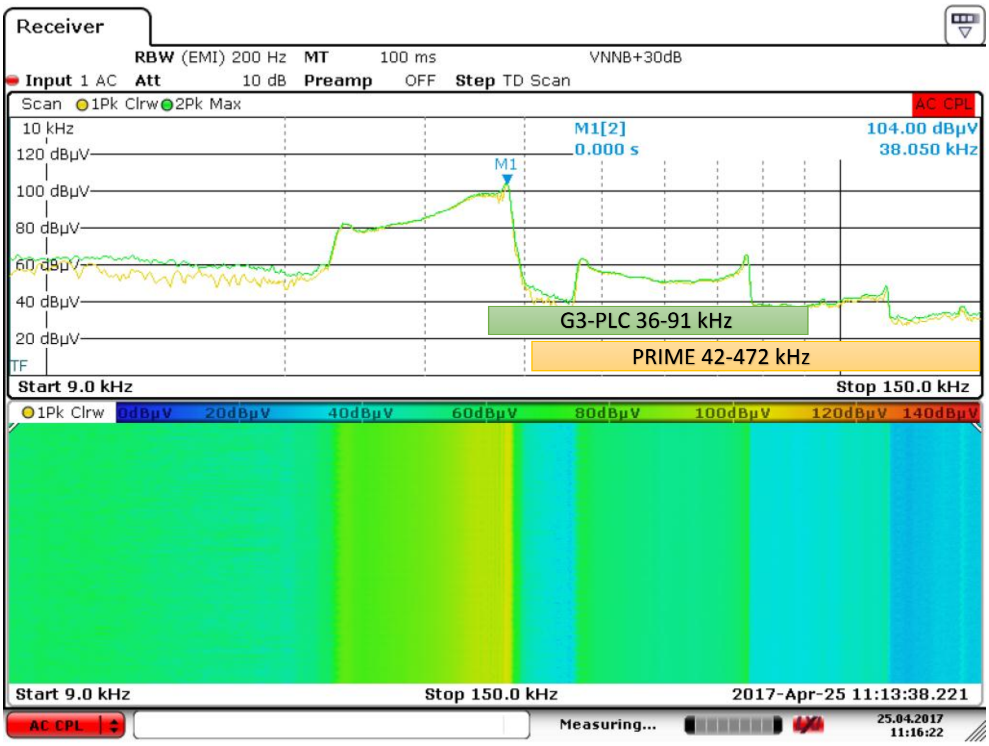
Even though some household appliances are reported emitting the disturbance in the frequency range 9 kHz to 150 kHz, but the existing standards which define emission limits are not completely applicable for all household appliances. So far, only lighting equipment and induction cooker limits are covered by the standard. Since nowadays many high-power household appliances apply the switching technology in their working principle, they may emit higher disturbances than it is emitted by the induction cooker and lighting equipment. The comparison of the highest disturbance produced by the sample of household appliances can be seen in Table. 7.3.

Table 7.3 The highest disturbance produced by the samples of household appliances

Nr.	Equipment Under Test	Highest Disturbance		
		Frequency	Level	
		(Hz)	(mV)	(dBuV)
1	Induction Cooker A	22300	4151.4	132.4
2	Induction Cooker B	37600	281.9	109.0
3	Inverter Microwave	21100	662.0	116.4
4	Conventional Microwave	20500	24.1	87.6
5	Mixer	9900	10.1	80.0
6	Hand blender	9600	2.1	66.6
7	Personal Computer	72100	3.2	70.1
8	Television (LED)	9000	4.0	72.0
9	Notebook	9000	8.5	78.5
10	Hair dryer	9000	9.5	79.6
11	Electric Massage	9000	2.2	66.8
12	LED Lamp	40500	7.2	77.2
13	Compact Fluorescent Lamp	51200	7.2	77.1

In Europe, narrowband power line communication in public utility wires is generally used in the frequency range within 3-148.5 kHz (CENELEC Bands) as defined in EN 50065 [31]. The PLC technology standard Powerline Intelligent Metering Evolution (PRIME) uses frequency range within 42-90 kHz while the competitor G3-PLC standard uses frequency range within 35-90 kHz as their main signaling frequency [32,33,34].

Considering the disturbance properties (level and frequency) produced by some household appliances and the possible negative effect of disturbance to the main signaling of existing narrowband PLC technology, an equipment like the inverter microwave should be considered to be regulated in the standard. The inverter microwave produced high disturbance level in the range of frequency that is used by narrowband PLC main signaling as can be seen in Figure 7.4. By regulating the appliance, the emission of the inverter microwave is expected to be reduced.



Date: 25.APR.2017 11:16:23

Figure 7.4 The emission of inverter microwave and the frequency range used by G3-PLC and PRIME mains communication signaling

Regarding to the emission of inverter based microwave, the disturbance level produced by inverter microwave tends to decrease over the time of operation. Figure 7.5 shows the disturbance level produced by inverter microwave for 5 minutes operation. The initial disturbance level of inverter microwave is 711 mV and it is getting down to 329 mV at the end of measurement. The highest disturbance level occurs in the beginning time of operation. This condition should be considered when performing emission test. The conventional test receiver requires some time to perform the emission test. Hence, the highest disturbance produced by the inverter microwave could not be obtained using conventional test receiver. The FFT-based test receiver is capable to measure the emission instantaneously so that the highest disturbance produced by inverter microwave at the beginning time of operation could be discovered. It is recommended to use FFT-based receivers in the emission test of inverter microwave.

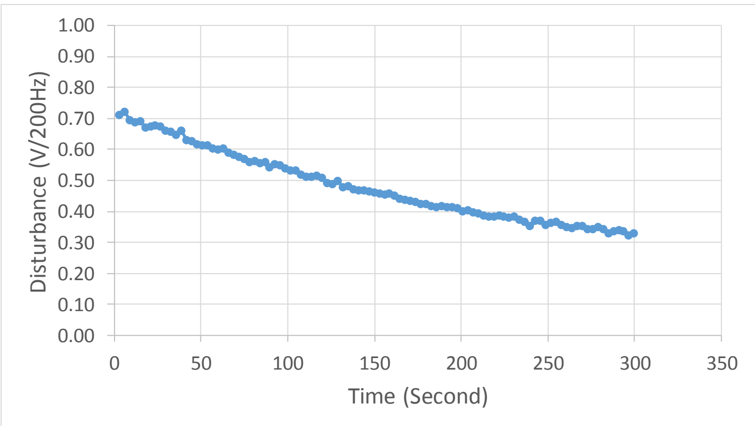


Figure 7.5 The disturbance level produced by inverter microwave for 5 minutes of operation.

CHAPTER 8
CONCLUSION AND FUTURE WORK

8.1 CONCLUSION

According to the measurement and simulation results, some conclusions related to the properties and behavior of disturbance produced by household appliances in residential network environment can be stated as follows:

1. The internal impedance of appliances is unique and influenced by several factors including the mode of operation (standby or operation mode). Some appliances that are equipped with internal filter may have very low impedance in the frequency range within 9-150 kHz. This internal impedance affects the disturbance occurred in the network.
2. The disturbances produced by some household appliances are affected by the mains voltage level. 3 types of disturbance behavior related to the variation of mains voltage levels are: constant, inverse and combination of linear and inverse relationship.
3. The neighbor appliances affect the disturbance occurred in the network through their internal impedance and power consumption properties. The neighbor appliances are classified into 4 groups based on their internal impedance and power consumption properties. The effects of each group of neighbor appliance to the disturbances are also depending on the internal impedance properties and disturbance behavior of the disturbance source appliance.
4. The disturbance source appliance, neighbor appliance, mains network impedance, mains voltage level and cable length-size affect the disturbance occurred in the mains network. The simulation of disturbance in residential network environment indicated some characteristics as follows

    - The possible disturbance distributions in the network are clearly affected by the network properties parameters.
    - For certain configurations of the disturbance source appliance, neighbor appliances, mains network impedance, mains voltage level and cable length, the disturbance appeared in the network could be higher than the disturbance generated by the appliance when it is operated individually.
    - The presence of neighbor appliance generally reduces the disturbance in the network, but the reduction level of each neighbor appliance is different from each other. When a low impedance appliance is not connected in one customer network (in residential network), a significant disturbance level could enter the distribution network.

5. The measurement and simulation results indicate some situations which may lead to a difference of disturbance obtained between the standard emission test procedure and the real network situation. Some considerations and recommendations regarding the existing standard emission test are as follows:

    - The disturbance produced by some appliances is affected by the mains voltage level. Hence, the emission test at different supply voltage levels is recommended.

- The disturbance occurred in the real network condition may be higher than it is measured in the standard test configuration. This is occurred when the mains voltage level drops due to the presence of neighbor appliance. The issue can be addressed by obtaining the highest possible disturbance produced by the EUT by varying the supply voltage level.

- Considering 3 factors, the disturbance level and frequency produced by the appliance, the existing standard emission limit for frequency range 9 kHz to 150 kHz and the frequency band that is used for mains signaling of AMR-PLC applications, the emission of inverter based microwave appliances should be considered to be regulated. Considering the disturbance behavior of inverter microwave that decreases over the time of operation, the use of FFT-based test receiver is recommended.

8.2 FUTURE WORK

Further research should be conducted to complete the work and get better understanding about the disturbance properties and behavior in the frequency range 9 kHz to 150 kHz as follows:

A. Observing the Behavior of Disturbance against Low Frequency Harmonic

The power quality of mains network is varying and depending on some factors including the power source properties and type of loads connected to the network. The power quality is related to the condition of voltage and current wave for fundamental frequency and other multiple frequencies below 2 kHz (low frequency harmonic). The IEC 61000-3-2 regulates the limit of voltage and current for low frequency harmonic in LV environment for specific type of load. The existence of low frequency harmonics may affect the disturbances produced by the appliances in the frequency range within 9-150 kHz. When the correlation characteristics between the disturbance and low frequency harmonics can be determined, then the parameter of low frequency harmonic content can be added to the parameter of simulation representing additional conditions of real residential network situation.

B. Non-Linear Behavior of Appliances.

The disturbances in the frequency range 9 kHz to 150 kHz emitted by one appliance will expose the neighbor appliances which are connected to the same network. This disturbance, due to non-linear behavior of neighbor appliances, may be converted into other disturbances in different frequency bands (could be in frequency above 150 kHz). The observation can also be conducted further for combination of various disturbance frequencies emitted by some disturbance source appliances.

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List of Figures

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Abbreviation

AMN : Artificial Mains Network

CDN : Coupling Decoupling Network

CFL : Compact Fluorescent Lamp

EUT : Equipment Under Test

FFT : Fast Fourier Transform

LED : Light Emitting Diode

PCC : Point of Common Coupling

PV : Photovoltaic

TDL : Touch Dimmer Lamps

MCS . Mains Communication System

CISPR : The Comité International Spécial des Perturbations Radioélectriques

CENELEC : The European Committee for Electrotechnical Standardization

PRIME : PoweRline Intelligent Metering Evolution

PLC : Powerline Communication

DIN : Deutsches Institut für Normung

EN : Europäischen Norm

IEC : The International Electrotechnical Commission

LV : Low Voltage

EMC : Electromagnetic Compatibility

R1D : Daytime Residential Mains Network

R1N : Nighttime Residential Mains Network

SW : controlled switches

PC : Personal Computer

RF : Radio Frequency

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